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MINUTES
OF THE TWENTY-SECOND EXPLOSIVES SAFETY SEMINAR

Volume I

Anaheim Marriott Hotel
Anaheim, California
26-28 August 1986

Sponsored By
Department of Defense Explosives Safety Board
Alexandria, Virginia

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DEDICATION

The 22d DoD Explosives Safety Seminar is dedicated to the memory of Dr. Thomas A. Zaker, member of the DDESB Secretariat from 16 March 1970 until his untimely death on 12 June 1986.

Dr. Zaker obtained his BS from Case Institute of Technology, Cleveland, Ohio and Master and PhD from Illinois Institute of Technology, Chicago, Illinois. Prior to his employment with the Federal Government, Dr. Zaker worked at the Illinois Institute of Technology Research Institute. He began his employment at the DDESB Secretariat as a Mechanical Engineer in charge of the Board's Explosives Safety RDT&E Program. In July 1984, he became the Director of the Technical Programs Division.

Through exceptional performance of duty, professional competence, devotion to duty and untiring efforts, Dr. Zaker significantly contributed to the accomplishment of the vital mission of the Department of Defense Explosives Safety Board. His vast knowledge and expertise in the field of explosives safety was recognized throughout the Department of Defense and international communities. He will be sorely missed by his co-workers and contemporaries.

PREFACE

This Seminar is held as a medium by which there may be a free exchange of information regarding explosives safety. With this idea in mind, these minutes are being provided for your information. The presentations made at this Seminar do not imply indorsement of the ideas, accuracy of facts presented, or any product, by either the Department of Defense Explosives Safety Board or the Department of Defense.

Volume I includes the following sessions of the proceedings:

BRUCE B. HALSTEAD
Colonel, USA
Chairman

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TABLE OF CONTENTS

Volume I

Cont'd

SESSION - INSENSITIVE ENERGETIC MATERIALS
Moderator - Mr. Kenneth R. Shopher

SESSION - BLAST VENTING EFFECTS NEAR STRUCTURES
Moderator - Mr. Charles N. Kingery

Cont'd pg. vi

SESSION - BLAST RESISTANT CONSTRUCTION DESIGN
Moderator - William A. Keenan

SESSION - EXPLOSIVES AND PYROTECHNIC SAFETY PROTECTION
Moderator - Melvin C. Hudson

SESSION - EXPLOSIVES SENSITIVITY TESTING
Moderator - Eric T. Olson

Cont'd p. vii

SESSION - BLAST RESISTANT CONSTRUCTION DESIGN II
Moderator - Dr. Sam A. Kiger

SESSION - EXPLOSIVES AND PYROTECHNIC SAFETY PROTECTION II
Moderator - Tom Kartachak

SESSION - ORDNANCE TESTING EFFECTS)

Cont'd pg. vii

Moderator - James F. Proctor

SESSION - BLAST RESISTANT CONSTRUCTION DESIGN III
Moderator - John L. Byrd, Jr.

GENERAL SESSION

cont'd

SESSION - UNDERGROUND EXPLOSION EFFECTS; cont'd pg ix
Moderator - Arnfinn Jenssen

Cont'd

SESSION - PERSONNEL HAZARDS;
Moderator - Edward A. Daugherty

SESSION - DETONATION PROPAGATION TESTING;
Moderator - Raymond E. Kreps

SESSION - CAUSES & EFFECTS;
Moderator - Carlo Ferraro, Jr.

Cont'd p. x

cont'd

SESSION - EXPLOSIVES SAFETY - THE OPERATIONAL ENVIRONMENT,
Moderator - Charles A. Cates

CHAIRMAN'S OPENING REMARKS

22d EXPLOSIVES SAFETY SEMINAR

Mrs. Pope, General Eckelbarger, General Bender, Commodore Reeves, Mrs. Zaker, Distinguished Guests, Professionals of the Explosives Safety Community, friends. Welcome to the 22d Explosives Safety Seminar. Our largest yet - 710 not included late registration. The fact that our goal for the next three days is to improve the quality of explosives safety through the active exchange of state-of-the-art information. Look around you. You see most of the explosive safety expertise available, not only from the United states, but also from 19 countries thru-out the world. Make the most of this great opportunity to compare notes, rub shoulders, and unite in pursuit of the awesome responsibilities each of us share. We depend very much on each other to find ways of meeting increasing requirements of military readiness with acceptable margins of safety in an environment of more potent explosives, limited real estate and even more limited financial resources.

It is now my pleasure to introduce to you the current members of the Explosives Safety Board. The Army is represented by Colonel Bill Parris from the Office of the Deputy Chief of Staff for Logistics, Department of the Army. The Alternate Board Member, Mr. Charles Cates is also here. Mr. Cates is from the Army Safety Center at Fort Rucker, Alabama. Captain Bob Wernsman is the Navy

Representative. Pressing duties in OP-41 of the Navy Staff prevent Captain Wernsman from attending. We are fortunate, however, to have the Navy's Alternate Board member here today, Mr. Carlo Ferraro. He is from the Explosives and Nuclear Weapons Safety Section in the Office of the Chief of Naval Operations in the Pentagon. From the Air Force, our newest member Colonel Chip Morrison. Colonel Morrison is the Chief of Weapons Safety, Air Force Inspection and Safety Center, at nearby Norton Air Force Base. Also from the same office, the Alternate Air Force member, the Chief of Explosives Safety, Mr. Ken Shopher.

I would now like to introduce our Keynote Speaker for the 22d Explosives Safety Seminar. Major General Donald Eckelbarger is the Director for Human Resources Development in the Office of the Deputy Chief of Staff for Personnel, Department of the Army. Graduating from the Military Academy and an Engineer by education, General Eckelbarger has followed the route of an artillery officer in his Army career. He has seen first hand the impact of our explosives safety standards on the lives of the soldiers in his commands and on operational readiness. As the Army's Director of Safety, he is imminently qualified to speak to us today on the Army's program, "Safe Army 1990." General Eckelbarger

BALANCING OPERATIONAL READINESS AND EXPLOSIVES SAFETY

KEYNOTE ADDRESS
BY
MG DONALD E. ECKELBARGER
DIRECTOR OF US ARMY SAFETY
22ND DOD EXPLOSIVES SAFETY SEMINAR
26 AUGUST 1986

I AM PLEASED AND HONORED TO HAVE BEEN INVITED TO ADDRESS THIS DISTINGUISHED GROUP OF EXPLOSIVES EXPERTS. THIS 22ND DEPARTMENT OF DEFENSE SPONSORED EXPLOSIVE SAFETY SEMINAR PROVIDES A UNIQUE OPPORTUNITY TO EXCHANGE INFORMATION AND TO DEVELOP IDEAS REGARDING ALL ASPECTS OF EXPLOSIVE SAFETY. COLLECTIVELY YOU REPRESENT MUCH OF THE FREE WORLD'S KNOWLEDGE AND EXPERTISE IN THIS FIELD. WHILE I WILL NOT ATTEMPT TO DISCUSS THE TECHNICAL ASPECTS OF YOUR PROFESSION, I DO WANT TO SHARE WITH YOU SOME THOUGHTS ON EXPLOSIVES SAFETY AS VIEWED FROM MY PERSPECTIVE AS DIRECTOR OF SAFETY FOR THE UNITED STATES ARMY.

OF THE MANY ELEMENTS OF THE ARMY'S OVERALL SAFETY PROGRAM, EXPLOSIVES SAFETY IS ONE OF THE MOST DIFFICULT. IT IS DIFFICULT BECAUSE A BALANCE MUST BE MAINTAINED BETWEEN OPERATIONAL REQUIREMENTS AND SAFETY CONSIDERATIONS. WE SOLDIERS MUST HAVE EXPLOSIVES -- MUNITIONS AND WEAPONS -- TO DO THE JOB. TROOPS TRAIN AND LIVE WITH EXPLOSIVES, WHERE INHERENT DANGER AND HAZARDS ARE THEIR DAY-TO-DAY COMPANIONS. COMMANDERS

MUST HAVE POLICIES, REGULATIONS, AND PROCEDURES -- RULES -- THAT WILL ALLOW THEM TO ACCOMPLISH THEIR MISSION, AND AT THE SAME TIME PROTECT THEIR SOLDIERS. THIS IS PARTICULARLY TRUE WITH FORCES THAT ARE PREPARED FOR FORWARD DEPLOYMENT WHERE SOLDIERS MUST BE ABLE TO LITERALLY ROLL OUT OF THEIR BUNKS, GET THEIR AMMUNITION AND MOVE TO TACTICAL LOCATIONS - READY TO FIGHT. THEREFORE, EXPLOSIVES SAFETY MUST SUPPORT THE ARMY MISSION, NOT IMPEDE IT.

THE NATURE OF MODERN WARFARE WITH ATTENDANT SMALL UNIT ACTIONS, HIGHLY FLUID BATTLEFIELDS, AND EXTENDED BOUNDARIES, COUPLED WITH THE USE OF ADVANCED WEAPONRY -- HIGH RATES OF FIRE AND INCREASED LETHALITY -- PUTS A PREMIUM ON QUICK RESPONSE. TO MEET THE REQUIREMENTS OF THIS BATTLEFIELD, WE DEPLOY HIGHLY SOPHISTICATED WEAPONS AND CONCENTRATE LARGE QUANTITIES OF EXPLOSIVES IN FORWARD AND DISPERSED AREAS. THIS CAN RESULT IN POTENTIAL RISK TO BOTH MILITARY AND CIVILIAN PERSONNEL, PROPERTY, AND EQUIPMENT. IN SUCH AN OPERATIONAL ENVIRONMENT, WHERE SOLDIERS, CIVILIANS, WEAPONS AND EXPLOSIVES ARE INTER-MINGLED, A SINGLE ACCIDENT COULD HAVE CATASTROPHIC CONSEQUENCES. IN ADDITION TO A POTENTIAL FOR THE LOSS OF LIFE AND DESTRUCTION OF PROPERTY, THERE IS THE POSSIBILITY THAT A MISHAP COULD GREATLY IMPAIR OUR ABILITY TO MAINTAIN GLOBAL COMMITMENTS.

FOR EXAMPLE, AN ACCIDENT INVOLVING THE PERSHING II MISSILE SYSTEM POSITIONED IN GERMANY CLEARLY DEMONSTRATES THIS POINT. ON 11 JANUARY 1985, DURING A ROUTINE TRAINING EXERCISE, A PERSHING II MISSILE MOTOR CAUGHT FIRE AS IT WAS BEING LIFTED OUT OF ITS SHIPPING CONTAINER.

THE ACCIDENT HAPPENED IN A LOCAL TRAINING AREA ABOUT 3 KILOMETERS EAST OF HEILBRONN, WEST GERMANY. THREE SOLDIERS WERE KILLED AND 16 OTHERS WERE INJURED. THERE WERE NO CIVILIANS, AMERICAN OR GERMAN, INVOLVED.

THE SEQUENCE WENT SOMETHING LIKE THIS. MISSILE HANDLERS WERE STARTING TO ASSEMBLE A LIVE MISSILE TAKEN FROM ITS STORAGE CONTAINER. IT WAS THE THIRD MISSILE ASSEMBLY OPERATION CONDUCTED THAT DAY. AS THE MOTOR WAS BEING LIFTED FROM ITS CONTAINER, AN ELECTROSTATIC DISCHARGE IGNITED THE ROCKET MOTOR WHICH THEN BURNED RAPIDLY FOR SEVERAL MINUTES. THERE WAS NO EXPLOSION. IN ADDITION TO THE SOLDIERS KILLED AND INJURED, THE MOTOR AND SHIPPING CONTAINER WERE DESTROYED, THE VEHICLE AND OTHER RELATED EQUIPMENT WAS DAMAGED.

AMERICAN AND GERMAN SAFETY OFFICIALS JOINTLY CONDUCTED AN EXHAUSTIVE INVESTIGATION TO IDENTIFY WHAT WENT WRONG. THIS EFFORT DETERMINED THE EXACT CAUSE OF THE FIRE AND CORRECTIVE ACTIONS HAVE BEEN TAKEN.

ALTHOUGH THERE WERE NO NUCLEAR WARHEADS OR NUCLEAR MATERIALS AT THE SCENE OR INVOLVED IN THE ACCIDENT IN ANY WAY, ACCIDENTS LIKE THIS CAN GREATLY UNDERMINE THE CONFIDENCE OF HOST COUNTRIES IN OUR ABILITY TO SAFELY MAN AND MAINTAIN OUR WEAPONS SYSTEMS.

ANOTHER EXAMPLE OF THE OPERATIONAL REQUIREMENTS OF MAINTAINING DEPLOYED FORCES WEIGHED AGAINST THE POTENTIAL RISKS OF ACTIVITIES INVOLVING EXPLOSIVES IS AN ACCIDENT WHICH TOOK PLACE HERE IN THE UNITED STATES.

IN 1985, A COMMERCIAL TRAILER TRUCK TRAVELING THROUGH OKLAHOMA, WAS TRANSPORTING 10 MARK 84 BOMBS DESTINED FOR

OVERSEAS. IT COLLIDED WITH A PRIVATE AUTOMOBILE ON A MAJOR INTERSTATE HIGHWAY. THE CAR CAUGHT FIRE AND SUBSEQUENTLY DETONATED SEVERAL OF THE BOMBS. THE EXPLOSIONS LEFT A 27 FOOT DEEP CRATER IN THE MIDDLE OF THE HIGHWAY. NEARLY HALF THE BUILDINGS IN A NEARBY TOWN WERE DAMAGED, AND MORE THAN 50 PEOPLE WERE INJURED. AS ONE WOULD EXPECT, THE EVENTS AND CIRCUMSTANCES OF THIS ACCIDENT RECEIVED NATIONWIDE TELEVISION AND NEWS MEDIA COVERAGE. THIS ACCIDENT CAUSED ANXIETY AMONG MEMBERS OF THE AMERICAN PUBLIC, JUST AS THE PERSHING MISSILE ACCIDENT CAUSED ALARM AMONG GERMAN CITIZENS.

THESE TWO ACCIDENTS SERVE TO UNDERSCORE THE FACT THAT ANY ACTIVITY INVOLVING EXPLOSIVES IS EXTREMELY SENSITIVE, AND A SINGLE INCIDENT CAN PRODUCE CATASTROPHIC RESULTS. ACCIDENTS SUCH AS THESE REMIND US OF THE NECESSITY FOR CONSTANTLY FOCUSING ON BETTER MEANS OF PROVIDING A SAFE AND SECURE ENVIRONMENT IN ALL ASPECTS OF THE EXPLOSIVES BUSINESS.

APART FROM THE OBVIOUS AND SINCERE HUMANITARIAN CONCERN FOR THE SAFETY OF SOLDIERS AND CIVILIANS, EXPLOSIVES SAFETY IS A KEY FACTOR IN TERMS OF READINESS. WE MUST SUPPORT OUR TACTICAL MISSION IN AREAS WHERE SOLDIERS LOAD AMMUNITION ONTO TACTICAL VEHICLES, TRANSPORT IT ON CIVILIAN HIGHWAYS, AND USE IT IN TRAINING. WE MUST ALSO MAINTAIN A HIGH DEGREE OF SAFETY IN MANUFACTURING, HANDLING, AND STORING OUR MUNITIONS TO INSURE A HIGH STATE OF COMBAT CAPABILITY.

BECAUSE OF THE INHERENT HAZARD POTENTIAL OF AMMUNITION AND EXPLOSIVES, IT IS EVEN MORE VITAL THAT NEW APPROACHES TO THIS ASPECT OF SAFETY BE DISCUSSED AND SUBSEQUENTLY DEVELOPED, AT MEETINGS SUCH AS THIS.

THE ARMY FULLY REALIZES THAT ITS EXPLOSIVES SAFETY PROGRAM HAS TO BE A BALANCE BETWEEN ONE THAT PROVIDES FOR TOTAL PROTECTION OF LIFE AND PROPERTY AND ONE THAT PERMITS FIELD COMMANDERS TO ACCOMPLISH THEIR MISSION OF TRAINING A COMBAT READY FORCE.

A POSITIVE SIGN OF THE ARMY'S COMMITMENT TO IMPROVING EXPLOSIVES SAFETY AND AN INDICATION OF THE HIGH ORDER OF ITS PRIORITY IS THE FACT THAT EVEN IN THIS ERA OF GRAMM-RUDMAN BUDGET CUTS, THE ARMY HAS FUNDED AN ADDITIONAL $30 MILLION FOR IMPROVING THE EXPLOSIVES SAFETY POSTURE FOR DEPLOYED FORCES. THIS MONEY, WHICH SURVIVED A HIGHLY COMPETITIVE DISTRIBUTION PROCESS, WILL BE USED TO BUILD PROTECTIVE STRUCTURES AND TO RELOCATE AMMUNITION STORAGE SITES AREAS AWAY FROM AREAS POPULATED BY SOLDIERS AND CIVILIANS.

TO FURTHER ENHANCE OUR ARMY EXPLOSIVES SAFETY PROGRAM, SEVERAL KEY ACTIONS HAVE BEEN TAKEN.

FIRST, WE HAVE PROVIDED EXPANDED ARMY EXPLOSIVES SAFETY TRAINING COURSES TO MEET THE WORLDWIDE NEEDS OF SAFETY SPECIALISTS AND SAFETY APPRENTICES. THESE TRAINING COURSES FOCUS ON DAY TO DAY MISSION REQUIREMENTS DEALING WITH THE STORAGE AND TRANSPORTATION OF EXPLOSIVES.

SECOND, WE ARE DEVELOPING RISK ASSESSMENT POLICIES SO THAT SAFETY PERSONNEL WILL BETTER UNDERSTAND MISSION REQUIREMENTS AND BE ABLE TO FULLY INTEGRATE EXPLOSIVES SAFETY INTO OPERATIONS, THEREBY ACHIEVING A SITUATION THAT COMPLEMENTS BOTH MISSION AND SAFETY.

THIRD, WE ARE WORKING TOWARD WRITING EXPLOSIVES SAFETY INSTRUCTIONS INTO OPERATION ORDERS SO THAT FIELD COMMANDERS WILL RECOGNIZE AND MINIMIZE RISKS DURING TACTICAL TRAINING.

FINALLY, WE ARE WORKING CLOSELY WITH ALLIES AND HOST COUNTRY OFFICIALS TO RESOLVE SPECIAL EXPLOSIVES SAFETY PROBLEMS WORLDWIDE. TOP ARMY OFFICIALS ARE INVOLVED IN REVIEWING AND SUPPORTING THESE INITIATIVES. THESE ON-GOING ACTIONS ARE A POSITIVE SHIFT TOWARD THE CONCERN FOR STRIKING A BALANCE BETWEEN OPERATIONAL READINESS AND EXPLOSIVE SAFETY.

BEFORE I FINISH, I WOULD LIKE TO BRIEFLY MENTION AN INITIATIVE THE ARMY HAS DEVELOPED TO IMPROVE ITS SAFETY PROGRAM. IN OCTOBER 1985, THE CHIEF OF STAFF ENDORSED A 5-YEAR PLAN ENTITLED SAFEARMY 1990. THIS LONG-RANGE STRATEGY CALLS FOR IMPROVEMENTS IN ALL ASPECTS OF SAFETY.

A KEY PART OF THIS PLAN CALLS FOR THE DEVELOPMENT OF A PROGRAM GOAL FOR EXPLOSIVE SAFETY. THIS GOAL PROVIDES FOR THE INTEGRATION OF SAFETY PRACTICES IN MOVEMENT PLANS AND OPERATIONAL PROCEDURES, ESPECIALLY THOSE RELATED TO PRE-POSITIONING AND PRE-STOCKING OF EXPLOSIVES. THREE OF THE KEY ACTIONS IN SUPPORT OF THIS GOAL ARE DEVELOPING AN AUTOMATED DATA BANK CONTAINING THE LATEST EXPLOSIVES HAZARD CLASSIFICATION DATA, ASSESSING THE IMPACT OF EXPLOSIVES SAFETY CRITERIA ON DEPLOYMENT OPERATIONS, AND EVALUATING THE OPTIONS FOR LOWERING THE LEVEL OF RISK.

BECAUSE EXPLOSIVES SAFETY IS NOW AN INTEGRAL PART OF SAFEARMY 1990, IT REMAINS A DYNAMIC, FLEXIBLE PROGRAM THAT CAN ADAPT TO CHANGES. MANY OF THESE CHANGES WILL BE STIMULATED BY THE WORK OF YOU AND YOUR COLLEAGUES.

IN LOOKING AT THE CONFERENCE AGENDA I WAS IMPRESSED WITH THE VARIETY AND IMPORTANCE OF THE SUBJECTS TO BE COVERED, THE DIVERSITY OF THE PARTICIPANTS, AND THE CHALLENGE YOU HAVE SET FOR YOURSELVES. I KNOW THAT EACH OF YOU WILL BENEFIT GREATLY FROM THIS CONFERENCE. IT CAN BE A SOURCE OF IDEAS WHICH WILL ASSIST GREATLY IN OUR SEARCH FOR NEW KNOWLEDGE, NEW TECHNIQUES, AND NEW APPLICATIONS. THE CHALLENGE BEFORE US IS TO MEET THE NEED FOR TECHNOLOGICAL ADVANCES IN THE DEVELOPMENT OF BOMBS, BULLETS, AND SHELLS THAT THE SOLDIER CAN "BEND, FOLD, AND SPINDLE", OR AS YOU USUALLY SAY, INSENSITIVE ENERGETIC MATERIALS. WE NEED BETTER BLAST-RESISTANT CONSTRUCTION, AND A SAFER MEANS OF HANDLING TRANSPORT AND STORING OF EXPLOSIVES. WE ALSO NEED PEOPLE WHO ARE INNOVATIVE IN THEIR APPROACH TO EXPLOSIVE SAFETY.

I AM CERTAIN THAT WHATEVER YOUR SPECIFIC INTERESTS ARE, THE NEXT THREE DAYS OF THE SEMINAR WILL AFFORD YOU THE OPPORTUNITY TO EXPLORE THEM PROFITABLY.

I WISH YOU EVERY POSSIBLE SUCCESS.

15 YEARS OF EXPERIENCE WITH RISK MANAGEMENT
A REVIEW FROM A MANAGEMENT PERSPECTIVE

by
Maj. Gen. U.F. Bender
Deputy Chief of Staff Logistics
Chairman of the Swiss Military Explosives Safety Board

ABSTRACT

In 1971 risk management was introduced in Switzerland for dealing with safety in the storage of ammunition. After briefly reviewing the development of safety regulations in Swiss ammunition storage and main features of the new safety concept, a review of fifteen years of first-hand experience from a management perspective is presented. General experience asserts that risk management requires

- special management involvement
- time and patience
- an atmosphere of multilateral trust and confidence

Practical experience with risk management shows that

- actual risks from ammunition storages in Switzerland were drastically reduced in the last 10 years at minimum cost
- under Swiss conditions, compliance with NATO safety principles would only lead to a marginal increase of safety, while causing large financial outlays
- needed additional manpower is relatively small while substantial savings in overall systems costs can be obtained
- the reaction of Swiss politicians were generally positive; risk management can also bring positive side effects in other areas.

INTRODUCTION

Exactly 15 years ago, the first quantitative risk analysis of an ammunition storage installation was presented to the Swiss Explosives Safety Board. This event was a major milestone in the history of Swiss explosives safety regulations. It inaugurated a transition phase from a traditional safety concept that was based on quantity-distance tables to a modern safety concept based on assessing quantitative risk values.

Fifteen years of first-hand experience with this new safety concept, and with problems presented by the transitional phase were collected since then. As chairman of the Swiss Explosives Safety Board, I can state that it has been a very positive experience. We have learned in these years a lot about the DO's and DONT's of the risk concept.

I intend with my talk to present to this distinguished audience several important experiences that were obtained in my country. Several presentations given at the last seminar, in 1984, especially the opening addresses by my colleagues from the British and Australian safety boards, demonstrated to me that other nations have also considered the introduction of similar concepts. Though each nation must adapt this concept to its own and special situation, our experience in Switzerland might help others in one way or another.

HISTORY OF AMMUNITION SAFETY REGULATIONS IN SWITZERLAND

Let me set out with a brief review of the history of Swiss regulations pertaining to ammunition storage. Up to the end of World War II, Switzerland lacked extensive regulations in this field. Though the responsible authorities knew that neighboring nations had established far more stringent regulations, our authorities trusted in the high quality of our ammunition and regarded major accidents as practically impossible. As a result, large storage facilities were built in close proximity to civilian installations.

Such thinking ended abruptly after World War II, when four consecutive accidents killed 19 persons and inflicted over 100 millions of Swiss francs of damage to the affected surroundings and to the installations, plus the loss of almost 10'000 tons of ammunition. The most spectacular and devastating event occurred in an underground installation on December 19, 1947, which killed 9 persons, when part of a mountain came down on a nearby village.

These events marked a first major milestone in the history of Swiss safety regulations. The Swiss Military Explosives Safety Board was established, and one of its first tasks was to work out new and more stringent regulations. In essence, the new regulations followed the traditional and widely accepted concept of safety-distances to inhabited buildings and to roads, and also the concept of various hazard categories.

Only a few years after the new regulations became effective, a number of problems arose:

- The amount of ammunition and its explosive content steadily increased;
- The military readiness requirement called for additional storage space closer to populated areas, and for mixed storage of various hazard categories;
- As urbanization of Switzerland steadily progressed, dwellings, industries and roads moved closer to existing installations.

In the mid 60ies, it became obvious that this situation permitted only three feasible alternatives:

1. Increasing the number of waivers from existing regulations;
2. Relocation of existing storages;
3. Development of new regulations based on a new safety concept.

The Explosives Safety Board realized that an increase of waivers would be "sticking one's head in the sand", while the financial resources necessary to relocate existing storage would be unavailable, aside from the difficulties in finding appropriate sites. The Board therefore decided at the end of the 60ies to investigate possibilities for working out new regulations. They were to be based on a safety concept that incorporates the following features:

- Quantitative assessment of actually expected damage from accidental explosions, through risk analysis, considering
  - . a realistic amount of explosives involved in an explosive event;
  - . a realistic analysis of explosion effects;
  - . a realistic and probabilistic prognosis of persons present in hazard zones;
- Realistic probability consideration of accidental explosions;
- Explicit criteria for acceptable risks;
- Cost-Benefit Analysis for improving the safety situation.

As my introductory sentence stated, the first experimental risk analysis of an underground installation based on this new safety concept was presented to our Board in 1971. After careful review, the Board decided to adopt this concept for the future, marking the second important milestone in the history of Swiss safety regulations.

The last 15 years were devoted to introducing this new safety concept. During an initial phase, research was sponsored to work out the technological base for risk analysis. It consisted of theoretical and experimental work, for simulating explosion effects as well as of realistically estimating probabilities of accidental events. In addition, research was sponsored to develop criteria for risk acceptance and for answering questions of risk acceptability.

In a second phase, the administrative framework was established. It consisted of elaborating detailed regulations for the administrative authorities; recruitment and training of personnel for performing risk analysis and development of computer code for facilitating numerics of risk analysis.

The third phase, still in progress, is devoted to the practical implementation of this concept in the storage system. It consists of step-by-step analysis of all existing storage installations. These analyses form the basis for deciding to which extent further use can be approved, and for measures to be taken to improve the safety situation. The authorities are allowed to switch to the new regulation and introduce mixed ammunition storage only when all these conditions are met.

REVIEW FROM A MANAGEMENT PERSPECTIVE

Our generally positive experience with risk management in ammunition safety does not mean that we lacked problems during the last fifteen years. We too had to recognize that risk management is not just another technical tool which you buy just once and then let the authorities use it. In many ways, risk management is also a new way of thinking about and of looking at your problems. It therefore needs management's special attention. Let me cite three points, which, based on Swiss experience, are of special importance in this context:

1. Risk Management Requires Management Involvement

The traditional safety concept based on quantity-distance tables is fairly easy to administrate and does not require much management involvement. Defining the appropriate quantity-distances is a purely technical task and - provided safety-distances are followed - the check is straightforward and may be left to lower-level authorities. A clear black-and-white definition exists between a "safe" and an "unsafe" condition. When switching to the risk concept, however, the dividing line between "safe" and "unsafe" conditions becomes blurred. Therefore, top level management must be involved when questions of value judgements or special technical issues are addressed such as the following:

- What safety goals should be established?
- What numerical values should be selected for the criteria of individual and collective risk?
- How can compatibility be assured between goals for ammunition safety and safety goals in other technical fields?
- Which trade-off between risk, costs, and military readiness are appropriate in actual cases of ammunition storage?
- Which numerical probability estimates of accidental explosions are appropriate?
- Which conditions must be met, and which measures must be taken to assure that the probability factor does not rise?

Based on our experience, we therefore recommend to set up a management structure which is capable of coping with such questions.

2. Risk Management Requires Time and Patience

Risk management requires time, both during the transitional phase from former regulations to risk-based regulations, and during the subsequent phase. The effort required to perform initial risk analyses for all of your current storage installations must not be underestimated: technical tools have to be prepared, skilled personnel must be trained and data have to be collected before even analysis work can start and which - depending on the local situation - requires varying time periods.

This initial work will usually be followed by sporadic future efforts. Risk management requires updates of risk analyses and a new assessment of the safety situation whenever the situation in affected surrounding areas changes. Keeping track of safety is therefore a continuous task.

Again, based on our experience in Switzerland, we recommend that all prospective risk management proponents set realistic goals regarding transition time, and to proceed along clear priority lines.

3. Risk Management Requires an Atmosphere of Multilateral Trust and Confidence

From the traditional safety-distances concept, even top level managers can read the required distances, e.g., to inhabited buildings, from the corresponding table in the regulations, and compare them to existing distances. Special skill, however, is required to check input data and numerics of a risk analysis, which is difficult, if not impossible, for higher management. The responsibility for accuracy of risk analysis, therefore, rests with the analyst. He can cheat by selecting wrong input data at random. Such "mistakes" are often difficult to uncover. For risk management to be truly successful, it thus becomes necessary for top management to amply support the executive authorities so that a basic atmosphere of trust and confidence will exist.

After hearing about these basic prerequisites of successful risk management, I can imagine that you will be asking: "Is it really worthwhile going for the risk concept?", "Do the benefits outweigh the efforts?". To answer these questions, I will, in the final part of my presentation confront you with our practical experiences and the results which we have gained in Switzerland since introducing risk management.

a. Comparing Risk Situations of Storages in 1975 and in 1985

Shortly after introducing the risk concept, a preliminary risk analysis was performed for all existing storage installations in order to obtain an overview of the safety situation and to designate priorities during the transitional phase. The result for one group of installations is schematically shown in this graph. Each bar represents one storage installation, while the height of each bar represents the risk as of 1975. This graph clearly demonstrates an unbalanced overall risk situation at a considerable number of storages with high risk values, as well as a large number of storages with medium and small risk values. Needless to say, the responsible authorities were much astonished when this picture was shown. Ten years later, in 1985, the overall risk situation of the same group of storage installations was again designated. This graph shows that most of the high risk situations have been eliminated, mostly by improved ammunition allocation to existing storage installations, but also through technical safety measures. The total cost of this program amounted to several million Swiss francs. Overall capacity of this group of storages remained approximately the same. We may thus state that thanks to risk management we were able to keep our storage capacity, and at the same time substantially improve our risk situation. Moreover, we have to keep in mind the increasing urbanization of our country during this decade. No doubt, a real and measurable success!

b. Comparing Swiss Regulations with NATO Safety Principles

A substantial amount of our reserve ammunition for the first readiness phase is stored in above-ground freestanding storage facilities, dispersed all over Switzerland. A clear comparison, between quantities allowed by our risk-based regulations, and by NATO regulations based on quantity-distance relationships, can be made for these types of storages.

I am, for example, taking a region in which 20 storage facilities are located. According to our regulations we are authorized to use 19 of them and to store a total of about 2100 tons of ammunition of mixed hazard categories. Only one storage proved to have an unacceptable safety situation. According to the total risk value resulting in this region, we would tolerate 1 fatality in about 1700 years, i.e. a fairly low risk according to our regulations.

Were we to apply quantity-distances of the NATO Safety Principles to the situation of these same 20 storages, only 7 of them could henceforth be used for storing ammunition of mixed hazard categories. The 13 remaining storages do not, in one way or another, comply with required minimum safety distances to inhabited building or roads. The storage capacity in this region would be reduced to about 500 tons of ammunition. This reduced capacity could only be somewhat increased if the various hazard categories were stored separately. This, however, would substantially decrease the required military readiness level. Therefore, we can conclude that complying with NATO Safety Principles would force us to build 20 to 25 new storages in order to meet the required total capacity of 2100 tons of ammunition in this region. Provided that we can find acceptable storage sites, it would cost up to 10 million Swiss francs, just for one particular storage region.

In this situation we have to ask the crucial question: "Would storage according to NATO Safety Principles provide more safety than storage according to the Swiss risk-based situation?" Based on detailed risk analyses for actual storage sites fulfilling NATO standards, and by comparison with the actual storage sites that fulfill Swiss safety criteria, we can answer that in this particular region NATO principles provide only a marginally higher safety than our regulations. Instead of the previously mentioned total risk value of 1 expected fatality in 1700 years, we would accept an overall risk of 1 fatality in 2200 years. This small difference is chiefly because NATO principles focus on the closest building or road only, and not on the total number of persons exposed to an accidental explosion, both in buildings, cars and in the open field.

Thus, we may conclude that, in Swiss conditions, compliance with NATO safety principles increases the safety only marginally, while necessitating considerable financial costs. Based on our experience, the risk-concept enables an efficient use of existing storage facilities while maintaining high safety and high military readiness levels.

c. Necessary Manpower for Implementing Risk-Management

At the present time, about 2/3 of all storage facilities are being operated according to risk-based regulations. Efforts to subordinate existing facilities to new regulations are slowly decreasing, whereas efforts to update the risk analysis continuously increase. Based on our experience so far, we expect that in the future 5 to 10 individuals will be required full time to administrate risk management for ammunition storages. They are responsible for updating analyses and for the technology base. Compared to the size of our ammunition storage system, and the total number of persons involved, we regard this as a small additional effort. Moreover, it is our experience that risk-management, as a consequence of better and more economical allocation schemes, resulted in saving manpower for operating the storages. Thus, we can definitely state that according to our experience in Switzerland, risk management costs no more than the traditional safety concept. In fact, our figures indicate substantial overall savings.

d. The Politician's Response to Risk-Management

In several instances, politicians as well as local authorities were exposed to the risk-management idea. While it would be unrealistic to expect unanimous acceptance of these ideas throughout the political spectrum, our experience showed that most politicians fully accepted this idea. In instances where local communities planned civil developments near existing installations, local authorities even got involved in the process of risk analysis by providing input data estimates. Consequently, they obtained a general understanding of safety problems and eventually agreed to this method as a basis for negotiations.

The positive reaction of the majority of politicians, as observed in Switzerland, is not really surprising. First of all, risk-management is a trade-off method for multiple objectives, i.e., of safety, money and military criteria in an openly demonstrable way. And making trade-offs is, after all, the way democracy works. Secondly, the militia system of the Swiss Army enhances understanding for defense problems and provides the essential basis of confidence in our defense system.

e. Positive Side-Effects of Risk-Mangement

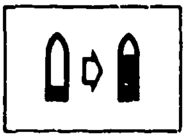
As mentioned earlier, risk-management is more than just another tool. It is also a new way of thinking. Risk-management requires systematic and rational thinking, a readily understandable and open demonstration of the problem and of ways to solve it and, lastly, it requires factor and criteria quantification, as well as cost-benefit considerations. All these aspects are, of course, not limited to the problem of safety of ammunition storage. As a positive side-effect of our work in ammunition storage, we have observed during the last few years that the underlying way of thinking has spread to other areas as well; first to the related area of ammunition and explosives manufacture, and recently also to such areas as military optimization and protection of military installations.

Ladies and gentlemen, each nation confronts its special situation. Thus, something benefiting one nation need not be equally effective for another. I suppose that this also applies to our experience with risk management. For us, it has been consistently positive and worthwile, and I hope that this will also be your future experience.

Thank you.

TURNING POINT TO A NEW SAFETY CONCEPT

INCREASING EXPLOSIVE CONTENT



MILITARY READINESS REQUIREMENTS

- **Storages Closer to Populated Areas**
- **Mixed Storage**

CONTINUING URBANISATION

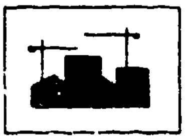
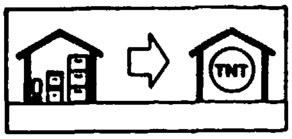


Figure 1

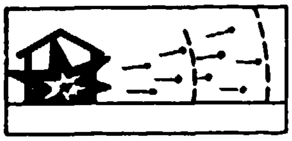
FEATURES OF NEW SAFETY CONCEPT

QUANTITATIVE ASSESSMENT OF ACTUALLY EXPECTED DAMAGE THROUGH RISK ANALYSIS

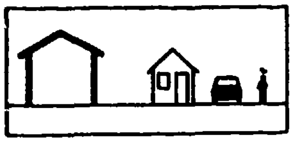
- **Realistic Amount of Explosives Involved in an Explosive Event**



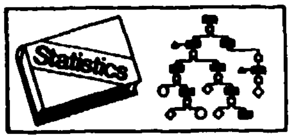
- **Realistic Analysis of Explosion Effects**



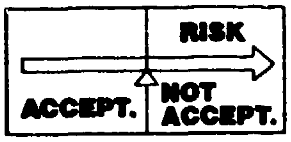
- **Realistic Prognosis of Persons Present in Hazard Zones**



REALISTIC PROBABILITY CONSIDERATION OF ACCIDENTAL EXPLOSIONS



EXPLICIT CRITERIA FOR ACCEPTABLE RISKS



COST-BENEFIT ANALYSIS

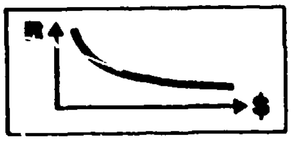


Figure 2

GENERAL EXPERIENCES WITH RISK MANAGEMENT

1. RISK MANAGEMENT REQUIRES MANAGEMENT INVOLVEMENT

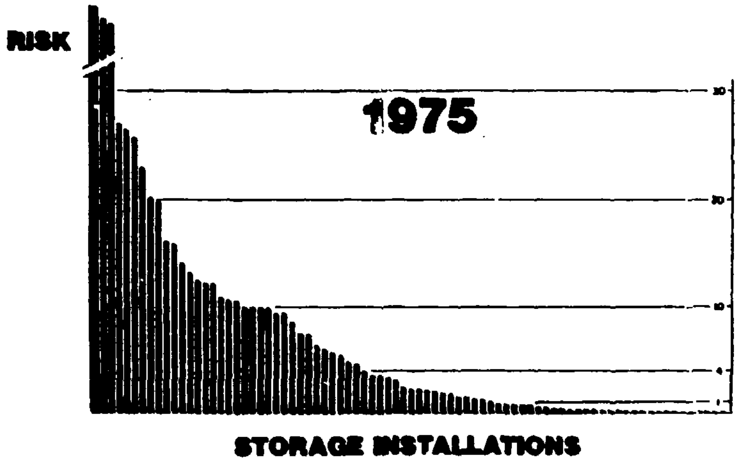
2. RISK MANAGEMENT REQUIRES TIME AND PATIENCE

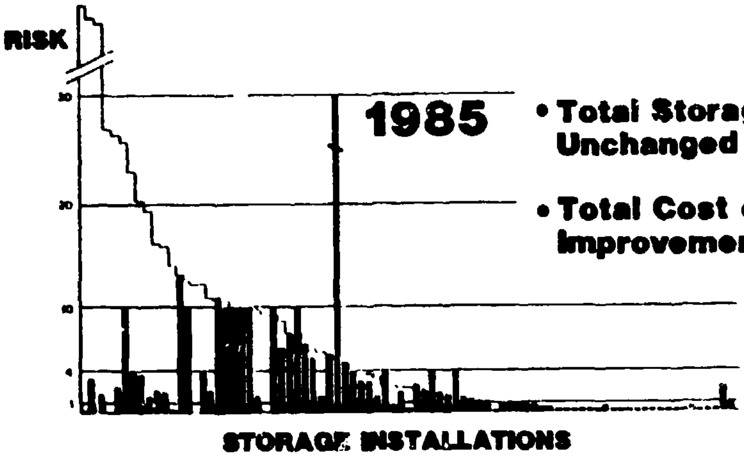
3. RISK MANAGEMENT REQUIRES AN ATMOSPHERE OF MULTILATERAL TRUST AND CONFIDENCE

Figure 3

PRACTICAL EXPERIENCES WITH RISK MANAGEMENT

COMPARING RISK SITUATIONS OF STORAGES IN 1975 AND 1985





- **Total Storage Capacity Unchanged**
- **Total Cost of Safety Improvement: 4 Mio SFr.**

Figure 4

PRACTICAL EXPERIENCES WITH RISK MANAGEMENT

COMPARING SWISS REGULATIONS WITH NATO SAFETY PRINCIPLES

- 20 Freestanding Storages in a Actual Region in Switzerland

- Required Storage Capacity in Region: 2100 Tons

COMPARISON	SWISS REGULATION	NATO SAFETY PRINCIPLES
Admitted for Ammunition Storage	19 ⌂⌂⌂⌂⌂ ⌂⌂⌂⌂⌂ ⌂⌂⌂⌂⌂ ⌂⌂⌂⌂☒	7 ⌂⌂⌂⌂⌂ ⌂⌂☒☒☒ ☒☒☒☒☒ ☒☒☒☒☒
Remaining Storage Capacity	2100 Tons ▮▮▮▮	500 Tons ▮
New Storages • Number	None	23 ⌂⌂⌂⌂⌂⌂ ⌂⌂⌂⌂⌂⌂ ⌂⌂⌂⌂⌂⌂ ⌂⌂⌂⌂⌂
• Costs	None	~10 Mio SFr.
Total Number of Storages	19	~30
Accepted Total Risk From All Storages	1 Fatality in 1700 Years ▮	▮ 1 Fatality in 2200 Years

Figure 5

ADDRESS

BY

COMMODORE PETER REEVES, MA CEng MIEE MRAeS ROYAL NAVY

MINISTRY OF DEFENCE

Chairman Defence Explosives Safety Authority

Chairman Explosives Storage and Transport Committee

Vice President, Ordnance Board,

London, England. SW6 1TR

at the

Twenty Second Department of Defense Explosives Safety Seminar,

Anaheim, California, USA

August 26th, 1986

ADVANCING TECHNOLOGY AND ITS IMPACT ON EXPLOSIVES SAFETY

Introduction

SLIDE 1 Ladies and Gentlemen, it is a great honour and pleasure to have been invited to speak at this 22nd Defense Explosives Safety Seminar. For that I thank Colonel Bruce Halstead and before him Captain Otis Brooks. My subject to-day is Advancing Technology and its impact on Explosives Safety.

'Stop the World I want to get off' is a well known saying and no doubt there are many in this hall today who have at one time or another have said just that. But technology is a remorseless juggernaut and hard taskmaster which does not accept complacency and just does not allow us to stop the world. Over the years, most nations have derived principles which if adhered to during weapon design and manufacture will enable the weapon to be assessed as safe and suitable for service and indeed, a harmonised set of such principles is currently being prepared within NATO. Similarly, national and international guidelines for the safe storage and transport of explosives and weapons have been generated. My talk will address the pressures these principles and guidelines are facing as a result of changing technology and then I intend to address what we in the UK are doing to face up to them.

It would be easy for a safety authority to lay down a set of principles by which a weapon will be judged for safety and then to say to designers either you obey them or your weapon will not get the clearances it needs to go into service. Such a rigid approach is only tenable if your rules are seen to be credible, relevant and cost-effective and in a world of advancing technology and increased competitiveness, this is rarely possible. Safety authorities have to be receptive to new ideas, though not so receptive as to be changing principles every time a new project or technical advance arises. We have to achieve a fine balance - if we are too conservative, we will be regarded as an irrelevant barrier to progress and a hindrance to weapon development - if we are too dynamic, our principles will have no stability or proven track record causing confusion and muddle and we would rightly lose credibility as a safety authority. Nevertheless the recent disasters in the world this year serve as a timely reminder that the glitter and seductiveness of technology can blind people to
SLIDE 2 safety can blind people to safety requirements and as examples I show two slides which record the disaster at Chernobyl and also here in the
SLIDE 3 US the tragedy of the Shuttle Challenger. To show you that danger is non discrimatory and that I am not being nationalistically selective,
SLIDE 4 the next slide shows UK's most notorious safety incident of the last 18 months - the Bradford fire where 60 people lost their lives and five times that number were injured due to the practise of out of date safety procedures.

BLANK Just as we in the military learnt a great deal from the USS Forrestal fire - indeed, many of the safety tests we now carry out on weapons stem from that incident - I am sure that many lessons will be learnt from these more recent disasters.

In the military explosives world, advancing technology is giving us increased missile accuracy and hence we are seeing a trend towards smaller warheads albeit with more energetic materials, together with larger and more energetic propellants to give the greater speeds and ranges being called for. The transcending trend, however, is in the advent of micro-computers. No self-respecting weapon is without its chips and software and more and more they are being used for safety critical functions in missiles and ammunition.

As a backcloth to these trends is the greater public awareness of safety generally - the increase in single issue pressure groups is testimony to the fact that western society is <u>not</u> prepared any longer to be treated paternalistically by those in authority but wish to be part of the consultative process, where the publics well being is concerned. This same public, on the other hand, is unhappy to see good farming or building land being left fallow because explosives quantity distance rules demand, on the grounds of public safety, that sufficient space be left to provide a safety zone surrounding explosives concentrations - a problem I suspect which is more acute in crowded Europe than here in the USA. Consequently, Safety Authorities have now to be even more careful and even more thorough in their deliberations and be prepared for their findings to be justified in open debate.

On the other hand, the industrial scene presents us with a conflicting pressure. Some 60% of UK's contracts these days are fixed price packages to cover development and the costs of the first production batch. Within these packages are the trials analysis and hardware needed to enable the safety authority to reach its independent judgement on safety. That judgement at the end of the day is subjective with the constraint that safety cannot readily be traded off against other parameters when either the money becomes tight or the schedule starts to slip. In the competition to win a contract, firms generally gamble on success-oriented programmes. If in the event, results of the trials are negative and thus have to be repeated after some modification to the design, budget problems arise. Consequently, commercial pressure is, in effect, for a lowering of safety standards - an inescapable fact, I fear, which is usually hotly denied by the companies themselves.

Nevertheless, it is my opinion that the public is winning the argument and higher standards of safety <u>are</u> being called for.

In support of that judgement, let me cite the demonstration of the safety of a nuclear waste container which was carried out by the UK's Central Electricity Generating Board in 1985. The aim was to show that the container was virtually indestructible. To this end, a train was obtained from British Rail and deliberately crashed into a nuclear fuel flask. The slides form a series of snapshots of the trial. The

SLIDE 5

SLIDE 6 train plus its three carriages weighed 250 Tonnes and the impact velocity was 100 mph. The flask was cuboid in shape, of side two and SLIDE 7 a quarter metres long, and weighed with its various ancillaries, some 48 Tonnes. After the impact it took five seconds for all the components involved in the crash to come to rest. The locomotive was crushed, the carriages were badly damaged but the nuclear flask was funtionally intact. The point about this demonstration was that it cost a considerable sum of money to stage and had very little scientific or engineering value. It was put on as a Public Relations Exercise for the media in order to get full TV and press coverage with the intention of favourably influencing public opinions towards the expansion of UK nuclear generating plant and reprocessing facilities. As the Chairman of the Central Electricity Generating Board said afterwards "In the past, people have had to take our word that these flasks are safe. Now they can see for themselves".

These factors of growing public awareness and industrial competition make it more important than ever, that those of us in the safety world anticipate new developments so that we are prepared accordingly when they are presented to us and that we react correctly taking due regard of public opinion as well as of military considerations. I am now SLIDE 8 going to describe some examples of current interest to the UK and I have chosen software, pyrotechnic initiated ammunition, seamines, submunitions and risk analysis as illustrative of the various aspects of the problems that face us. Let me start with that most dramatic of post war developments, namely electronics and software.

Software

There have been several recent weapon designs in which safety has been invested in software. A particular example is software based safety and arming mechanisms in guided weapons and gun ammunition. UK design principles decree that these mechanisms should be designed such that, and I quote, "No single circumstance can result in arming until the specified arming distance is reached". This implies the use of at least two safety features which are independent and which are operated by separate stimuli.

Micro-computers and software providing safety functions can meet this criterion, provided one of the safety breaks is not a semi-conductor, but even so we have had to develop a new approach for validating the software where it is in effect providing one of the safety features. Consequently, the UK Ordnance Board gathered together a cross-section of the software expertise that was available and as a result of their deliberations, guidelines were produced. As far as safety critical SLIDE 9 software is concerned two important aspects are highlighted - the design of the software so that it can be audited by an independent authority and the assessment itself. With regard to the design, several principles have been evolved but essentially it comes down to two main points.

Firstly, There should be a rigorous software requirement specification mathematically defined stating unequivocally the required functions of the software. This must be followed by a system design specification stating how the system shall perform the required functions, subdividing it down as necessary into program modules. These in turn must have their own mathematical requirement specification and associated design specification.

Secondly, A risk analysis shall be carried out module by module and configuration control and documentation shall be to the highest standards.

As for the assessments, discovery of software errors has been achieved traditionally by a combination of pre-delivery dynamic testing - that is, carrying out tests with a range of inputs and monitoring the outputs for correctness - and post-delivery customer misfortune. However, exhaustive testing is considered to be neither theoretically nor financially possible, while partial testing is inconclusive. Consequently, we have decided that when we are assessing safety critical software, we will use static analysis techniques supplemented where necessary by some dynamic testing.

Let me say something about static analysis. Static analysis is a technique for finding errors in computer programmes without actually running them. On the control front, it will reveal false entry points, including unreachable instructions, unwanted exit points including those known to the trade as black holes etc. As far as data is concerned, it will identify data used but not set, data set but not later used and so on. On the semantic front, it reveals algebraic formulae relating output to input and these may be compared with the specification. Thus, software bugs will have been systematically rooted out before the software is used in anger in a quick, effective and economical manner.

Nevertheless, we still believe it advisable to carry out a limited amount of dynamic testing after the static analysis but such testing will be minimal and only sufficient to confirm that the software indeed functions as intended and has been effectively debugged.

It cannot be over emphasised that a precursor to this approach, is the need for rigourously structured software in a modular form. Indeed, our current major activity in this field is persuading industry and our contractors who are being required to operate in a very competitive climate to adapt to this approach with the discipline it implies.

The static analysis techniques I have described are the culmination of a decade of research at the Royal Signals and Radar Establishment at Malvern and at Southampton University. Two sets of software tools are now commercially supported: MALPAS marketed by Rex, Thompson and Partners of Farnham, Surrey and SPADE marketed by Program Validation Ltd of Southampton. For maximum efficiency these tools should be used during the actual software development process and it is claimed that the checking out procedure is ten times faster than the writing process.

Having a set of proven software is only of benefit to safety, if the hardware it runs on is also functionally correct. Work has been progressing in the UK on the formal specification of hardware and the mathematical methods - methods using the same static analysis concept as for software - which are needed to prove that the implementation of such specifications are correct under all circumstances. This has lead to the development of VIPER, a new 32-bit micro-processor, specifically designed for safety applications and with software which is particularly amenable to static analysis. Many safety, arming and fuzing systems, however, do not require the complexity of microprocessor based systems, but the same techniques of hardware verification are equally applicable to custom VLSI designs. I do have some handouts on the static analysis tools, MALPAS and SPADE, which I will be pleased to hand out to anyone interested.

Pyrotechnic Initiated Ammunition

SLIDE 10

As the second example, I have chosen pyrotechnic initiated ammunition which is at the cheaper, mass-produced end of the weapon scale in contrast to the expensive guided weapons which tend to have the type of software about which I have just spoken. Pyrotechnic initiated ammunition, is usually of the smaller calibre variety (12mm-40mm) whose warhead is initiated on impact, by the heating of the initiating compositions in the nose. This in turn acts as a booster to the main charge. These initiating compositions are more sensitive than Tetryl and according to the safety principles to which the UK work, should therefore be separated from the main charge by a mechanical shutter. Clearly, in this type of ammunition which does not even have a Safety and Arming mechanism, this criterion is not being met. Consequently, to avoid throwing out the concept which has the advantage of being cheaper and more effective than its conventionally fused HE equivalent, we are carrying out a set of safety and environmental trials which of necessity need to be more extensive than for conventionally fuzed HE ammunition. If after this thorough examination, we are satisfied that the pyrotechnic initiated ammunition is no less safe than the conventionally fused round, we will of course pass it. In the course of this work, other related aspects have been highlighted. For example, the use of impact sensitivity as the dominant criterion upon which to assess the sensitivity of an explosive composition in relation to Tetryl has been called into question. The advent of Pyrotechnic Initiated Ammunition has certainly stirred up much debate in the UK and elsewhere on the wider issues of sensitivity of explosives and the UK is now prepared to use, where appropriate, a range of tests to assess the explosive sensitivity of a composition in the actual configuration in the armament in which it will be used.

Sea Mines

SLIDE 11

Changing track now to the sea or more specifically undersea. I would like to address the safety problems associated with sea mines. I don't suppose many of you know much about the intricacies of International Maritime Law but we have had cause to look into it reasonably closely because of UK's interest in modern Sea Mines.

The Hague convention No VIII of 1907 and other subsequent international agreements require that dangerous mine fields must be declared, and that subsequently, after the requirement for them ceases, they must be made safe. However, one of the operational characteristics which has been made possible by modern technology, is for a mine to remain inactive and therefore safe to shipping for a controlled but variable period after deployment with the aim - so the argument goes - that it's presence need not be declared until shortly before it is made active. During that interim period, shipping of various nations may pass within the lethal zone, so it is clearly essential that any such mine should have a very high level of safety during it's inactive period. Similarly, a very high level of reliability is required for the sterilisation facilities that are being asked for - namely facilities which enable an armed minefield to be 'switched off' and in due course be declared safe.

There is no doubt that mines can be designed these days which can be switched on and switched off at will and do other clever things using modern technology, but the serious international implication of an undeclared mine exploding will require special consideration by any Government wishing to deploy such live mines in the inactive state without declaring them. Acceptability of such an action will depend very much on the circumstances prevailing at the time. We do not believe safety authorities can determine how safe is safe under these circumstances. For this reason, the UK are taking the line that we will assess the safety of the mine during the inactive period and sterilisation period against the same standards as we use for the mine before its deployment from the parent vehicle. It is then the Governments' and its military forces perogative to interpret such a statement in what ever manner they see fit, in the light of the political and military situation pertaining at the time.

Sub-munitions

SLIDE 12

So-called maintenance free weapons is another development which modern technology is now making possible and as an example I have chosen sub-munitions. I define sub-munitions as the smaller munitions contained in one larger weapon. Typical are the airfield runway destruction weapons such as the UK's JP233 which is loaded as one weapon onto the aircraft and when over the target fires off a multitude of sub-munitions, some to crater the runway and the rest to act as anti-personnel devices. A modern trend with these and other such complicated weapons is to take advantage of the greater reliability of modern electronics in the laudable attempt to design them as 'wooden' rounds so that once they have left the factory they require no maintenance. The inability to breakdown such munitions has implications for safety because there is no reasonable way in which the sub-munitions can undergo a surveillance programme for safety in the course of its life. Incorporation of modifications, disposal of munitions at the end of their service life and investigation of munition defects and accidents, all require the munition to be broken down. As this has implications for safety we are suggesting to designers that means of access into weapons needs to be provided even if it means returning the weapon to a base depot or even the original manufacturer.

Risk analysis

SLIDE 13 As a final example and leaving the consideration of individual weapons, I wish to change to the area of mass storage of weapons and introduce the work we are doing on risk analysis. I mentioned in my opening remarks how the application of quantity distance rules could cause conflict with the public whom they are designed to protect, by making demands on scarce land resources. Consequently, we have put in hand a so called Hazard and Risk study with the Royal Military College of Science. The aim of the study is to derive a methodology for use when licensing an explosives facility which introduces a 'risk' factor into the assessment. At present the quantity distance rules assume that at some time an explosion will occur but protects the public by ensuring that the resulting effects of the explosion are confined within a 'cordon sanitaire'. Dr Rees will be describing these procedures in his talk on quantity distances later in the seminar.

Of course, there are things you can do to make an exploding mass safe or at any rate safer. Technology, using such principles as unitisation of stores, new building designs, chemicals to quench liquid propellant explosives, has advanced to an extent whereby there are practical means of reducing quantity distances if you are prepared to pay for them. To some extent this means putting a price on safety, which may appear cold blooded where human lives are concerned but it has to be done for any hazardous activity where the budgets are limited. The settlement in the Bhophal disaster in India will, I believe, cost Union Carbide at least $350m. If the company had replaced the safety equipment along the lines of the research to which they contributed had inidcated, they would have spent only about $1m and killed far fewer people - such is the wisdom of hindsight.

It is this trade off between the cost of accidents political as well as financial against the cost of their prevention which is at the centre of hazard and risk assessment. Crucial is the estimation of the likelihood of an accident occuring in the first place together with an agreed definition of what is an acceptable risk. I am not going to comment on the matter any further as Professor Hartley who is leading the UK study on the derivation of a risk methodology, is presenting a paper on the subject later in the conference.

Conclusion

BLANK SLIDE Let me sum up. I have given some examples where technology is taking us into uncharted seas and there are many other areas on which time does not permit me to dwell. Nevertheless, I hope you have been able to obtain some understanding of how we in the UK are responding to the challenge of remaining a credible safety authority in an age where public awareness and sensibilities need to be increasingly taken into account, where industrial competition is becoming fiercer and where technology is forcing us to look into new methods of working and new standards.

Future

What of the Future? The competitive element these days in weapon procurement contracts has accelerated a long standing post World War II trend of reducing the hardware available for safety trials and consequently a greater reliance having to be placed on paper analysis, modelling and assessments. In the old days, it was possible to use a statistically significant number of rounds of ammunition, say, to give a practical demonstration of safety but sophisticated and expensive stores such as Guided Weapons and torpedoes have made this quite impractical and for some time now, we have had to be content with having perhaps just one store available for a particular safety test such as the 12m drop. The results of such tests can at best only give safety authorities a warm feeling in their stomach that their judgement is correct. In recognition of this trend, I would like to see work going ahead on two fronts. First, much more R&D effort put into methods of prediction of weapon safety characteristics. The aim should be to arrive at a situation whereby the study of the chemical and physical properties of an explosive, its containment within a weapon and the environment with which it has to contend, could lead to a confident prediction as to its response to fire or dropping or whatever without actually having to destroy expensive hardware in the process. In fact, we are already some way down the road as we can predict with reasonable precision how long some explosive stores must be exposed to, for example, a fuel fire before an energetic reaction is produced, and it may be possible before very long to predict how violent that reaction will be. Secondly, in the tests that we do have to carry out, we need to ensure that we get the maximum information out of the tests not only by better instrumentation and by non-destructive techniques but also by interpreting safety in its widest sense, so that even when stores safely withstand a drop or a fire we know by what margin that safety was achieved. The data obtained from this second thrust would of course, support the first. My scientific colleagues tell me that I am an impractical misty eyed idealist and that there really is no substitute for trials. So ladies and gentlemen, I leave you with that challenge and thank you for listening to me so patiently.

SLIDE 14

GOOD MORNING LADIES AND GENTLEMEN,

AS THE DEPUTY ASSISTANT SECRETARY OF DEFENSE FOR FAMILY SUPPORT, EDUCATION AND SAFETY, IT IS INDEED MY PLEASURE TO SEE SUCH A LARGE ATTENDANCE AT THIS IMPORTANT EXPLOSIVE SAFETY SEMINAR. THIS TURNOUT IS PARTICULARLY GRATIFYING TO ME BECAUSE THE PURPOSE FOR MY BEING HERE TODAY IS TO PRESENT A POSTHUMOUS DOD SERVICE AWARD TO THE INDIVIDUAL TO WHOM WE ARE DEDICATING THIS SEMINAR, DR. THOMAS A. ZAKER.

BEFORE I CONTINUE, LET ME ASSURE YOU THAT I HAVE ABSOLUTELY NO INTENTION OF "PREACHING TO THE CHOIR." I RECOGNIZE THAT GATHERED HERE TODAY ARE SOME OF OUR BEST TECHNICAL ADVISORS AND EXPERTS IN THE FIELD OF EXPLOSIVE SAFETY. I WILL TAKE ADVANTAGE OF THIS OPPORTUNITY, HOWEVER, TO REPEAT SOMETHING THAT I'M SURE YOU ALREADY KNOW - THAT WE RELY HEAVILY ON YOUR TECHNICAL EXPERTISE. I AM THEREFORE VERY HAPPY TO SEE YOU HERE TODAY. YOUR ATTENDANCE AT THIS SEMINAR INDICATES A HIGH LEVEL OF COMMITMENT AND DESIRE TO KEEP ABREAST OF CURRENT DEVELOPMENTS IN YOUR FIELD. AS INFORMATION IS SHARED DURING THE VARIOUS SESSIONS OF THIS SEMINAR, THE KNOWLEDGE YOU WILL GAIN AND THE USE OF THAT KNOWLEDGE BACK AT YOUR ACTIVITY WILL, I AM SURE, MAKE MY JOB EASIER.

THE DEVELOPMENT, MANUFACTURING, STORAGE, TRANSPORTATION, HANDLING AND DISPOSAL OF AMMUNITION AND EXPLOSIVES, SAFETY IS A RESPONSIBILITY OF PARAMOUNT IMPORTANCE TO ME AND TO THE

ASSISTANT SECRETARY OF DEFENSE FOR FORCE MANAGEMENT AND PERSONNEL, MR. CHAPMAN B. COX. WE STRONGLY SUPPORT YOUR EFFORTS AND THOSE PROGRAMS WHICH CONTRIBUTE TO THE OPTIMUM DEGREE OF SAFETY ASSOCIATED WITH ALL ASPECTS OF THE PRODUCTION, HANDLING, AND CONSERVATION AND TRANSPORTATION OF AMMUNITIONS AND EXPLOSIVES.

THE DOD EXPLOSIVES SAFETY PROGRAM ATTEMPTS TO PROVIDE THIS DEGREE OF SAFETY BY PROVIDING A DISCIPLINED APPROACH TO IDENTIFY, EVALUATE, AND ELIMINATE OR CONTROL HAZARDS WITHIN TWO MAJOR CONSTRAINTS OF OPERATIONAL EFFECTIVENESS, TIME AND COST.

EXPLOSIVES SAFETY PROFESSIONALS LIKE DR. ZAKER AND YOURSELVES, BOTH IN GOVERNMENT AND IN INDUSTRY, CONTRIBUTE SIGNIFICANTLY TO THE DEFENSE OF THIS NATION. YOU DO THIS THROUGH THOSE EFFORTS THAT LEAD TO A LONG-RANGE EFFECT ON THE AMMUNITION AND EXPLOSIVES PRODUCTION BASE AND OUR NATIONAL RESOURCES, COMBAT CAPABILITY, AND RESPONSIVENESS WHICH ARE ESSENTIAL IN MAINTAINING THIS COUNTRY'S DEFENSE POSTURE. EXPLOSIVES SAFETY PROFESSIONALS TRULY DESERVE A GREAT DEAL OF THANKS AND APPRECIATION FOR WHAT THEY HAVE ACCOMPLISHED. WHEN YOU STOP TO CONSIDER THE LARGE NUMBER OF WEAPON SYSTEMS WE HAVE WITHIN DEFENSE, THE RELATIVELY LOW FREQUENCY OF MISHAPS AND THEIR LIMITED EFFECTS WHEN THEY DO OCCUR, CLEARLY INDICATE THAT WE ARE DOING A LOT OF THINGS RIGHT BUT THERE IS ALWAYS ROOM FOR IMPROVEMENT - ONE LIFE LOST IS TOO MANY. THE INDIVIDUAL WE HAVE DEDICATED THIS SEMINAR TO AND WHO WE ARE HONORING TODAY HAS PLAYED A MAJOR ROLE IN THIS ACCOMPLISHMENT.

I WOULD LIKE TO BRIEFLY ADDRESS SEVERAL ELEMENTS WITHIN THE EXPLOSIVES SAFETY PROFESSION AND HOW THEY RELATED TO DR. ZAKER'S CAREER. THESE ELEMENTS ARE ENGINEERING AND SAFETY STANDARDS.

IT IS IMPOSSIBLE TO OPERATE ANY PROGRAM WITHOUT SPECIFIC GUIDELINES. THE SET OF EXPLOSIVES SAFETY STANDARDS IS OUR GUIDE FOR OPERATING AN EFFECTIVE EXPLOSIVES SAFETY PROGRAM. TO BE EFFECTIVE, STANDARDS DO NOT HAVE TO BE CARVED IN STONE, BUT THEY MUST BE DYNAMIC AND ABLE TO CHANGE AS KNOWLEDGE AND EXPERIENCE ARE GAINED FROM SCIENTIFIC AND ENGINEERING PROGRAMS. IN CONSIDERING THE ENGINEERING ELEMENT, THAT ASPECT OF ENGINEERING WHICH FIRST COMES TO MIND IS THAT WHICH IS CONCERNED WITH BALANCING OPTIMUM SAFETY WITH EFFECTIVENESS AND COST IN THE AREA OF FACILITY SITES, DESIGN, CONSTRUCTION AND LAYOUT OF OPERATIONS. EQUALLY IMPORTANT, HOWEVER, IS THAT ASPECT WHICH DEALS WITH THE MACHINERY, EQUIPMENT, TOOLS AND MATERIALS USED IN THE LOGISTIC LIFE CYCLE OF AMMUNITION AND EXPLOSIVES.

DR. THOMAS A. ZAKER, DURING HIS SIXTEEN YEARS ON THE DEPARTMENT OF DEFENSE EXPLOSIVES SAFETY BOARD, WAS ACTIVELY INVOLVED IN THE CONTINUOUS IMPROVEMENT OF OUR EXPLOSIVES SAFETY STANDARDS. HIS VIGOROUS EFFORTS IN THE INTEREST OF EXPLOSIVES SAFETY ADVANCED OUR NATION'S DEFENSE IN TWO IMPORTANT WAYS - BY ENHANCING READINESS AND SAFETY AND BY REDUCING COSTS.

BY INCORPORATING INTO THE STANDARDS QUANTITATIVE DATA OBTAINED FROM THE RESULTS OF TESTS AND STUDIES SPONSORED BY

THE EXPLOSIVES BOARD, DR. ZAKER REFINED THE EXPLOSIVES SAFETY QUANTITY-DISTANCE STANDARDS FOR EARTH-COVERED MAGAZINES. THE PURPOSE OF THESE STUDIES, WHICH WERE CONDUCTED UNDER HIS DIRECTION, WAS TO ACCOUNT FOR THE STRUCTURAL DEBRIS HAZARD WHICH RESULTS FROM SMALL QUANTITIES OF EXPLOSIVES AND FOR THE SUPPRESSION OF AN EXPLOSIVE BLAST BY THE EARTH'S COVER. IN APPLYING THE FINDINGS OF THESE STUDIES, DR. ZAKER ALSO DEVELOPED EXPLOSIVES SAFETY QUANTITY-DISTANCE STANDARDS FOR DOD AMMUNITION AND EXPLOSIVES ACTIVITIES IN THEATERS OF OPERATION OUTSIDE THE UNITED STATES WHERE GROUND AND AIR UNITS ARE REQUIRED TO MAINTAIN A HIGH STATE OF READINESS. THE APPLICATION OF THESE STANDARDS WILL RESULT IN SAFER AND MORE ECONOMICAL UTILIZATION OF STORAGE FACILITIES.

DR. ZAKER ALSO DEVELOPED RECOMMENDATIONS FOR METHODS OF CONTROLLING EXPLOSION EFFECTS. UNDER HIS GUIDANCE, PRINCIPLES WERE ALSO ESTABLISHED FOR THE PROTECTION OF WORKERS ENGAGED IN THE PROCESSING AND MANUFACTURING OF AMMUNITION AND EXPLOSIVES FROM THE BLAST, FRAGMENTS AND THERMAL HAZARDS OF SUCH MATERIALS. AS A RESULT, SAFETY STANDARDS WERE ISSUED REQUIRING PERSONNEL PROTECTION FROM SUCH HAZARDS THROUGH FACILITY AND EQUIPMENT DESIGN FEATURES.

UNDER DR. ZAKER'S LEADERSHIP, THE EXPLOSIVES SAFETY BOARD TECHNICAL PROGRAMS DIVISION SUPERVISED AND COORDINATED THE EXTENSIVE REVISION AND EXPANSION OF THE TRISERVICE DESIGN MANUAL, "STRUCTURES TO RESIST THE EFFECTS OF ACCIDENTAL EXPLOSIONS." THIS MANUAL, FIRST ISSUED IN 1969, IS A HIGHLY REGARDED STANDARD REFERENCE FOR DESIGNERS OF STRUCTURES TO RESIST EXPLOSION LOADS. THE NEW COVERAGE AND METHODS WILL RESULT IN SIGNIFICANT ECONOMIES IN FUTURE DESIGNS OF FACILITIES FOR AMMUNITION STORAGE AND IN THE MANUFACTURING OF AMMUNITIONS WITHOUT COMPROMISING EXPLOSIVES SAFETY.

AD-P005 302

INSENSITIVE HIGH EXPLOSIVES EVALUATION TECHNIQUES

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ABSTRACT

The Air Force Armament Laboratory (AFATL) is developing an insensitive high explosive (IHE) for use in general purpose bombs. IHE will improve operational readiness by increasing munitions storage density at no additional risk. IHE candidates are tested for thermal stability, shock sensitivity and initiability prior to full scale testing. Subsequent full scale evaluation includes the following series of tests:

- Sympathetic detonation test;
- Fast cook off (Bonfire) test;
- Slow cook off test;
- Sled impact test;
- Bullet impact test;
- Fuel fire test; and
- Arena performance testing,

The Air Force uses state-of-the-art instrumentation techniques to accomplish these tests. This paper describes these techniques and test procedures leading to the IHE qualification of explosives.

AD PA 86-233

INTRODUCTION

The maximum amount of explosives permitted at any location relative to inhabited buildings and public traffic routes is prescribed by the quantity/distance (Q/D) requirements in AFR 127-100 (Reference 1). In populated regions and in areas where real estate is limited, Q/D criteria severely restrict the quantity of munitions stored on Air Force Installations. The primary concern in these areas is mass detonation of munitions stockpiles. As shown in Table I, the introduction of Insensitive High Explosives (IHE) ammunition into the inventories will significantly increase the allowable storage quantities, thereby improving operational readiness and sustainability.

TABLE I. STORAGE ADVANTAGES OF IHE

Quantity	Structure	Present Radius to Inhabited Building	IHE Radius to Inhabited Building
500,000 lbs	Igloo/Bldg (IHE)	3970 ft	600 ft
MK82 Pallet	Open	1240 ft	65 ft

To be labelled as IHE ammunition, an explosive item must be able to withstand any severe environment to which it might be exposed during its life cycle without accidentally detonating. Additionally, an IHE item must be able to survive the detonation of an intentionally detonated item without sympathetic detonation. These environments are simulated by the qualification tests for IHE ammunition (Reference 2). These tests and the corresponding required results are shown in Table II. The required results are characterized in the following manner.

A detonation is the most violent reaction achievable by an explosive item. It produces the maximum possible air shock, resulting in blast and fragment damage. In a detonation, all of the contained explosive participates in the reaction and the casewall is broken into small, highly stressed and sheared fragments. A detonation is a propagating reaction; it can be transferred from one item to another.

An explosive is not as severe as a detonation. Nonetheless, it results in a violent pressure rupture of the munition casewall and air shock. Larger fragments and unreacted or burning explosives are typically recovered from an explosion. This type of reaction is non-propagating.

The burning reaction required in the slow cook off is relatively mild. An explosive item which burns produces no casewall fragments. The system merely vents and the explosive is consumed in place.

TABLE II. IHE AMMUNITION CRITERIA

Test	Required Result
Bullet Impact	No Detonation
Sled Impact	No Detonation
Fast Cook off (Bonfire)	No Detonation
Slow Cook off	No Detonation or Explosion
Propagation	No Propagation of Detonation in Storage Configuration

In addition to the five tests listed, the Air Force also performs a fuel-fire fast cookoff to determine item survivability in this high temperature setting and arena tests to characterize the overall effectiveness of items filled with candidate explosives.

The U.S. Air Force methodology for developing and testing IHE candidates is the subject of this article. The evaluation techniques, which employ state-of-the-art instrumentation to acquire the necessary parameters, are discussed in detail.

DEVELOPMENT PROCESS

The Air Force development strategy for Insensitive High Explosive (IHE) candidates is illustrated in Figure 1.

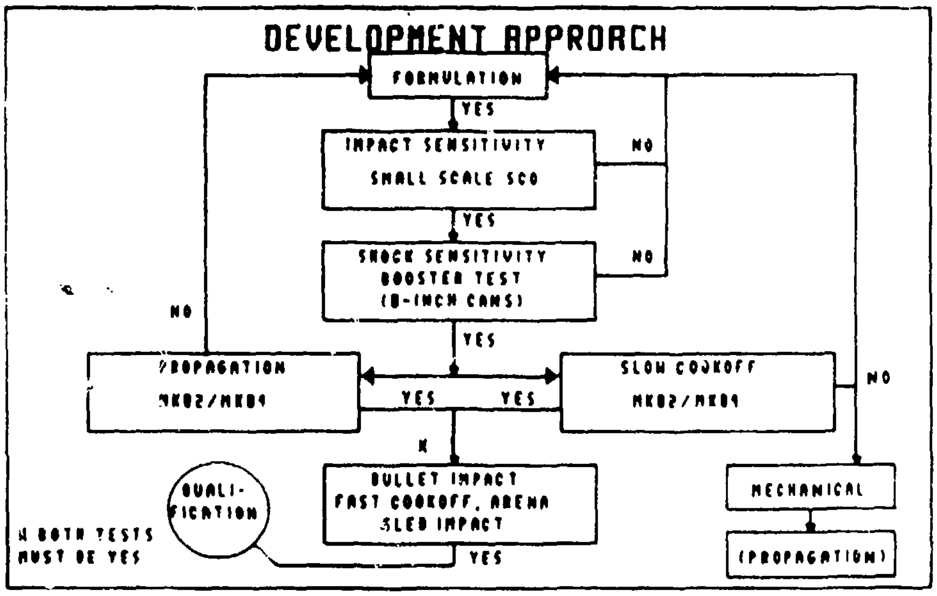


Figure 1. Insensitive High Explosives Development Cycle

A team of chemists and chemical engineers conduct processing studies and chemical compatability experiments (Differential Scanning Calorimetry, Chemical Reactivity Tests, Thermogravimetric Analysis, and Henkin Time-To-Explosion experiments) on very small explosive samples during the formulation process. Impact sensitivity tests are then conducted with a 5-kg drop hammer.

Data from these experiments are reviewed by a safety committee. The committee's approval grants authority to perform a one liter cook off. This cook off is conducted to confirm the predicted time to explosion and critical temperature. Scale up is attempted only upon confirmation of the parameters measured in the small scale tests.

Intermediate scale tests are conducted next to further characterize the experimental explosive. Shock sensitivity and booster tests are performed in 8-in.-diameter cans to ensure the formulation of interest can survive realistic shock inputs and remain reliably initiable. Critical diameter is established to ensure that the formulation is detonable and the measurements of shock sensitivity are valid. Modest changes in the formulation are allowed during this phase of testing to achieve the desired sensitivity/booster thresholds.

Once a baseline formulation meets the threshold requirements, full scale testing can begin. Sympathetic detonation and full scale slow cook off are considered the most critical tests and are conducted first. The bomb fill must pass both of these tests before proceeding with bullet impact, fast cook off, arena (performance) and sled impact testing. (If the formulation has difficulty surviving the slow cook off test in the existing hardware, mechanical modifications to provide pressure relief may be attempted (Reference 3). When all of the IHE criteria prescribed by DoD-STD-6055.9 are achieved in single item tests, the multiple item qualification tests are addressed.

This development approach provides an efficient method for downselecting from several candidate formulations. It is the dynamic product of lessons learned over years of explosive development. This methodology greatly abbreviates the normal interim qualification process since those explosive systems under consideration as IHE are mixtures of well characterized explosives. A more cautious approach is employed for those candidates which lack a significant development basis.

SHOCK SENSITIVITY

The response of an explosive formulation to shock inputs define its survivability in sympathetic detonation scenarios. This response is determined by the amplitude and duration of the input pulse. For general purpose (GP) bombs, the duration of the pulse seen by the acceptor bombs in sympathetic detonation scenarios is relatively long. Conventional small scale shock sensitivity experiments do not adequately simulate these long duration pulses. Foster, et al. (Reference 3) have developed an 8-in.-diameter heavily confined gap test to better model the large scale propagation environment (see Figure 2). The Air Force Armament Laboratory (AFATL) uses this evaluation technique extensively to characterize the shock sensitivity of its insensitive high explosive candidates before proceeding to large scale testing.

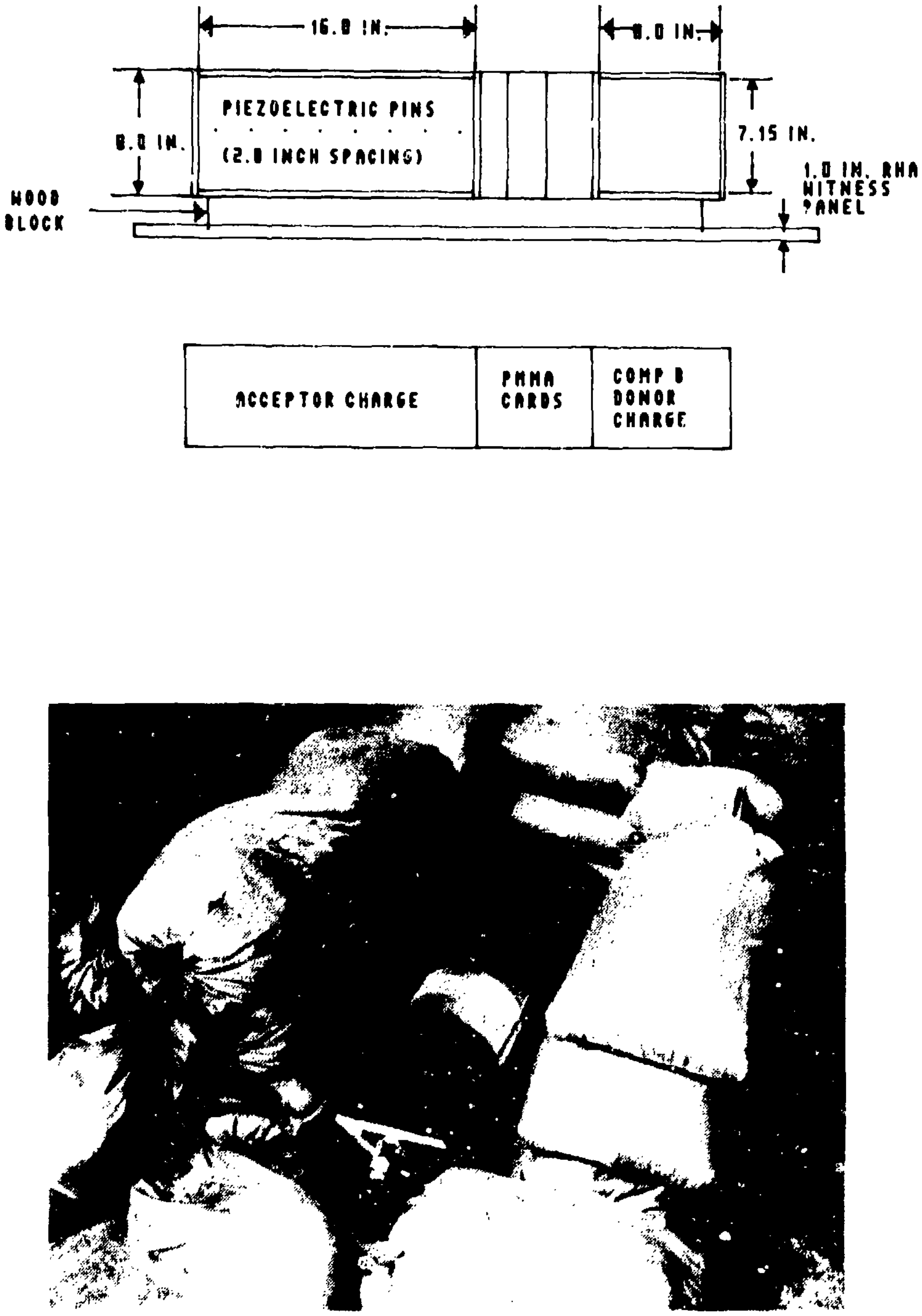


Figure 2: Set-up for the 8-inch-Diameter Gap Test

In this test, both the donor and acceptor charges are confined in 8.00-inch OD steel cases with 0.35-inch-thick casewalls. The charges are positioned horizontally resting on a grooved woodblock. The donor charge is 8 inches long and contains approximately 18.5 lbs of Comp B explosive. The acceptor charge is 16 inches long and its explosive weight is a function of the formulation density (generally 30-35 lbs of HE). The endplates on these engineering scale units are 0.5-in.-thick steel and are fastened to the cylinders using plastic bolts.

Polymethylmethacrylate (PMMA or plexiglas) cards are placed between the endplates of the donor and acceptor charges as shock attenuators. Varying thicknesses of PMMA present different levels of shock to the acceptor charge. The numerical pressure values corresponding to these thicknesses or gap widths are calculated using the HULL hydrodynamic code. The technique for arriving at these values is discussed in detail in "Suppression of Sympathetic Detonation," Proceedings of the 22nd Explosive Safety Seminar, August 1983 (Reference 4).

Representative data from these calculations are presented in Figure 3. The pressures shown are the calculated centerline pressures seen at a point 0.5 inches into a EAK (Density=1.61 g/cm^3, $\underline{U}s$=2.657 x 10^5 cm/sec, Los Alamos) acceptor.

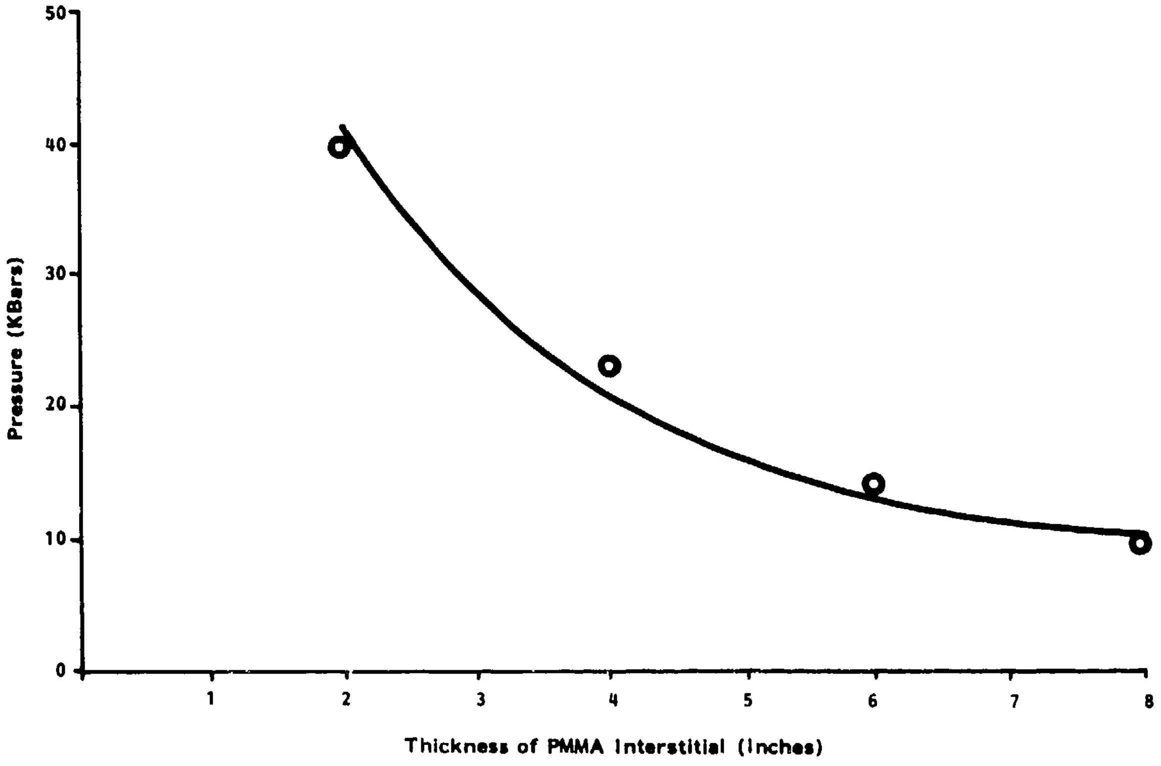


Figure 3. Centerline Pressure Pulse of EAK Acceptor (1/2-inch into EAK)

When endplates are not present between the donor and acceptor charges, the wave entering the acceptor is not exposed to the discontinuities introduced by the endplates. Figure 4 shows a comparison of data calculated with endplates in place and data calculated with no endplates. The values presented are calculated at the end of the PMMA gap prior to the interface with the acceptor endplate or explosive surface. It must be noted that the impulse duration is significantly longer when endplates are in place than when they are removed.

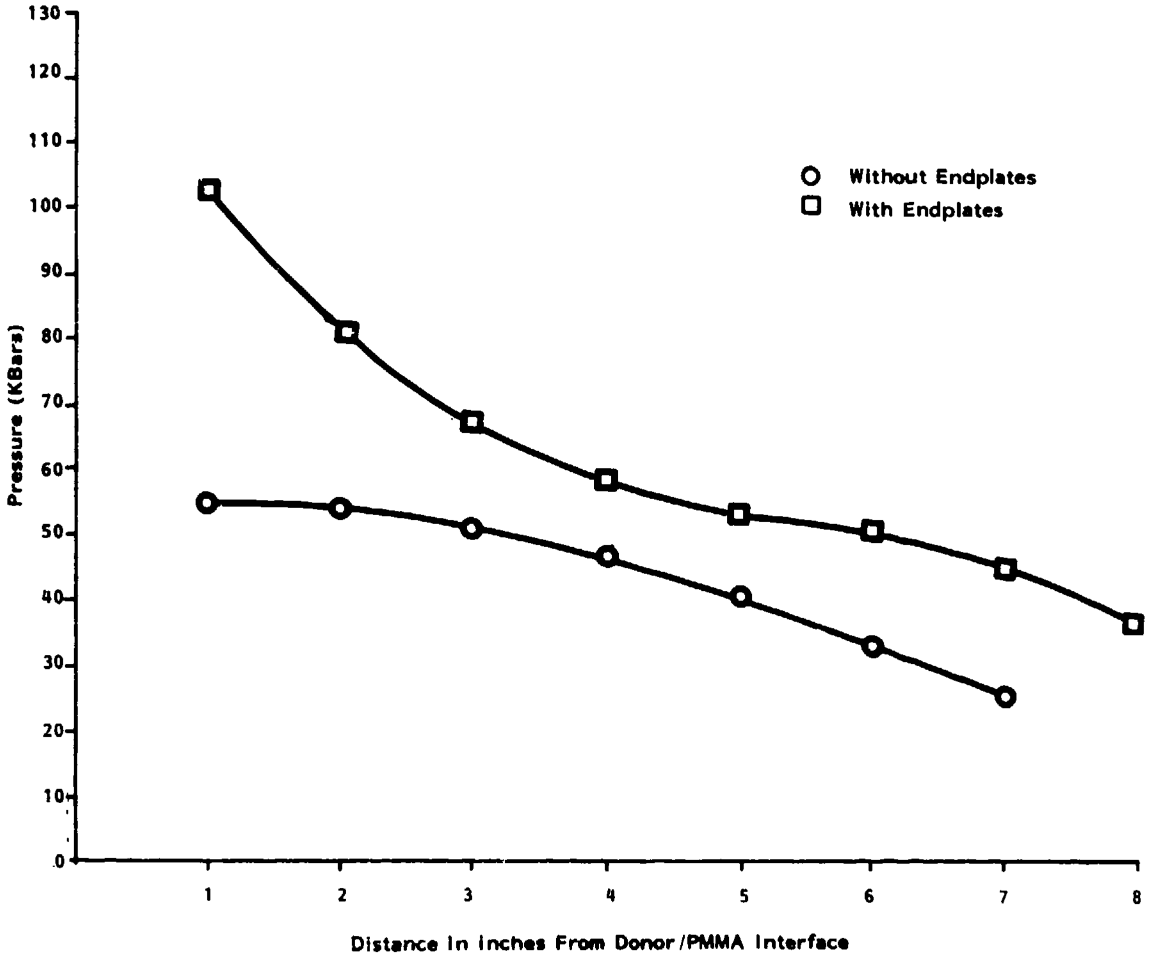


Figure 4. Shock Wave Pressure at the End of the PMMA Gap in the 8-inch-Diameter Gap Test

The degree of reaction from the acceptor charge is determined from an extensive but elementary data analysis. Piezoelectric time of arrival pins (Dynasen Inc., CA-1136) are placed at 2.0-inch intervals along the acceptor charge to monitor the velocity of the reaction front. As the shock wave passes, electrical signals from the pins are recorded by 20 MHz HP5180 transient digital recorders (Figure 5).

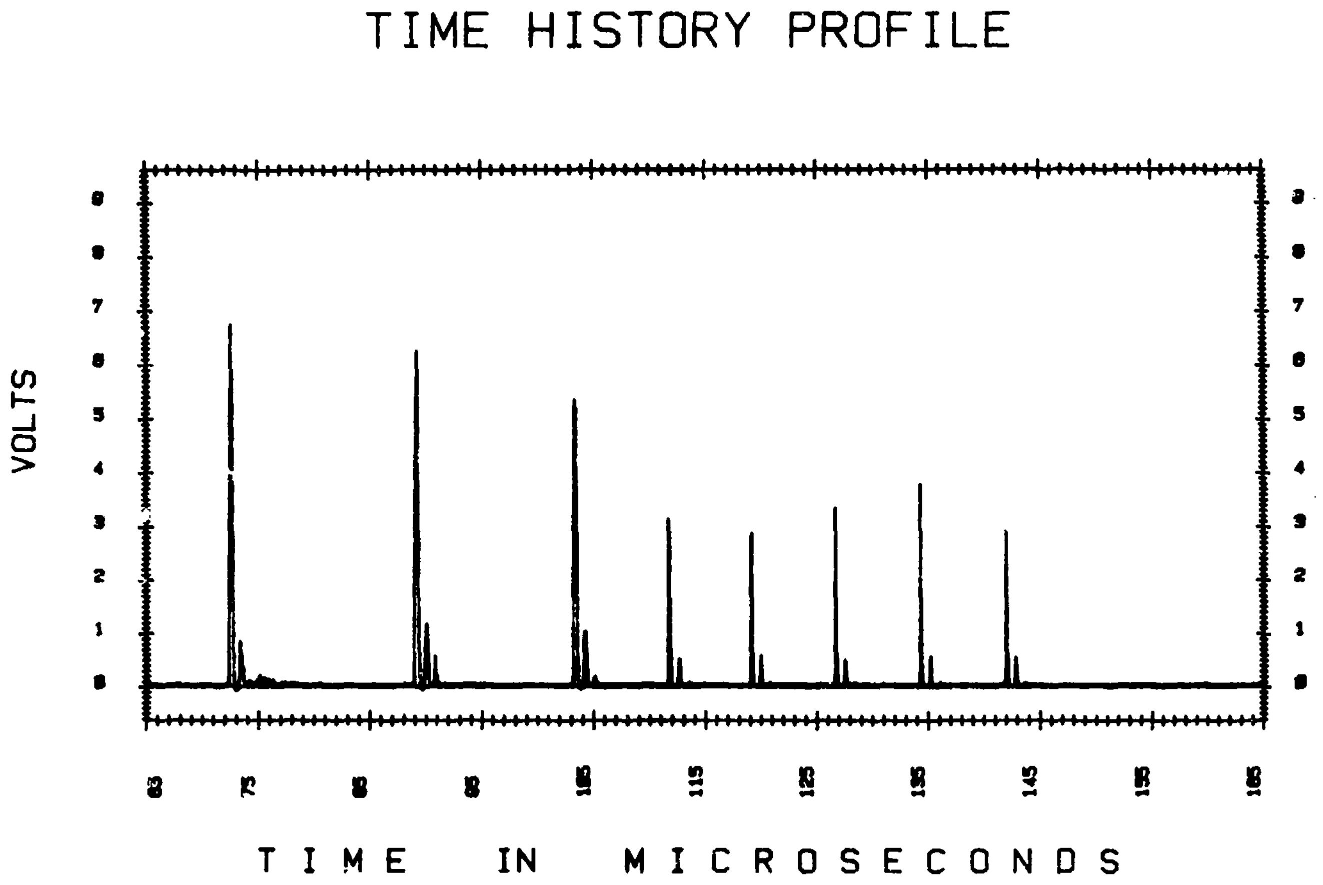


Figure 5. Typical Recorder Output

The records from these signals are confirmed by witness plate markings and case fragments. Transition to detonation is evidenced by signatures generated from high velocity casewall fragments impacting the rolled homogeneous armor (RHA) plate and the "burn" mark on the belly fragment (the fragment generated from the portion of the acceptor casewall resting on the grooved wood block).

Additionally, the fragments from the acceptor become notably stressed, thin, and highly sheared as steady state detonation is obtained (Figure 6).

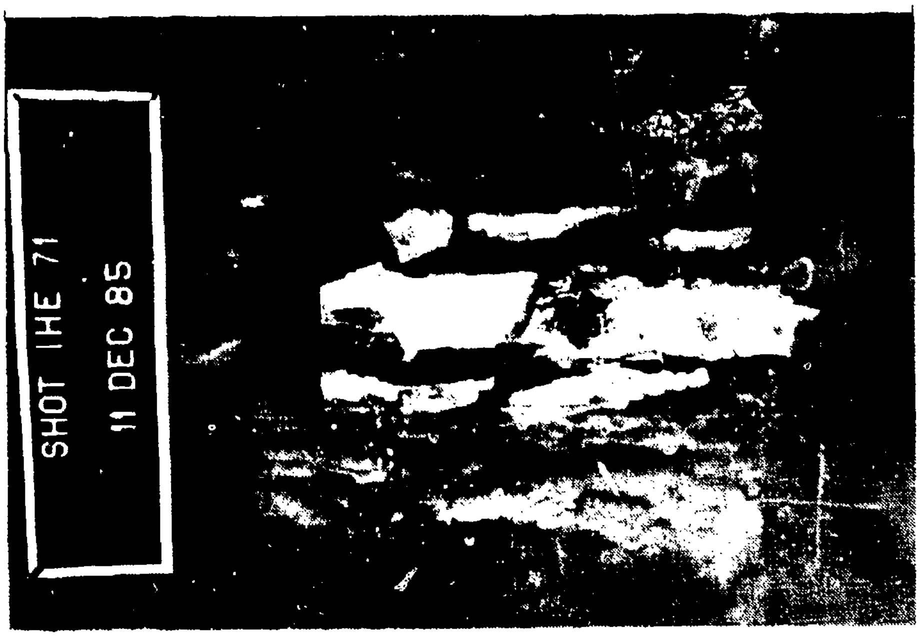


Figure 6. Fragments From a Detonated Acceptor Charge. Note the "burn" mark indicating the transition to detonation.

When the detonation of the donor charge does not propagate to the acceptor, the latter leaves no markings on the witness panel. The casewall fragments show no signs of high stress of adiabatic shearing. The fractures observed are typical of pressure bursts. Additionally, unreacted explosives are often recovered from the test arena after "no goes" (Figure 7).

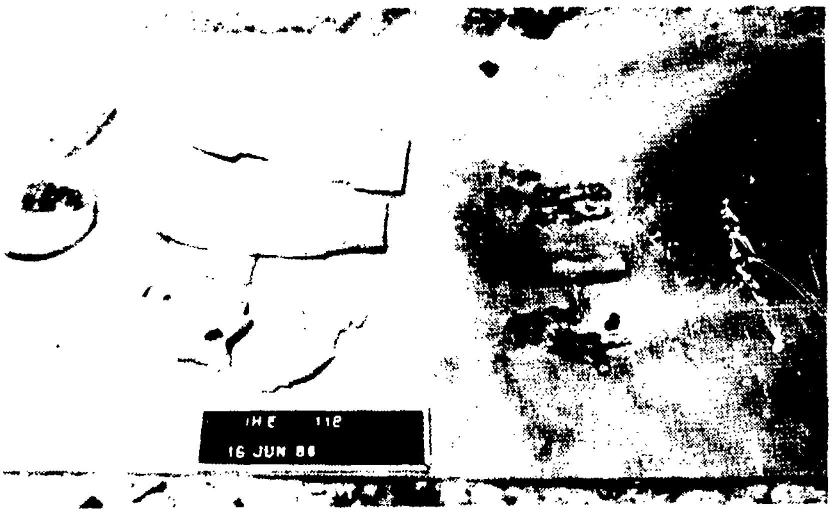


Figure 7. Post Test Remnants From a Non-Detonating Acceptor Charge.

At this point, there is not a large enough data base available from the 8-inch-diameter gap test to directly correlate shock sensitivity with survivability in full scale sympathetic detonation scenarious. That is, a maximum level of shock sensitivity, above which explosive formulations cannot survive full scale sympathetic detonation without propagation has not yet been established. IHE candidate melt cast formulations which have demonstrated sensitivity to shock inputs of between 42 and 65 KBars, (2 and 3 inches of PMMA) with endplates in place and between 45 and 50 KBars (6 and 7 inches of PMMA) with no endplates between the donor acceptor charges in the 8-inch-diameter gap test, have survived full scale propagation tests without detonating.

Currently, an explosive system is not taken to the full scale propagation arena without demonstrating an insensitivity to shock inputs of at least 40 KBars. A full scale sympathetic detonation versus 8-inch gap test data base is presently being compiled for several of the Armament Laboratory's melt cast IHE candidate systems.

Shock sensitivities obtained for representative explosive systems are provided in Table III.

TABLE III. SHOCK SENSITIVITY VALUES FOR VARIOUS EXPLOSIVES

Explosive	Go/No Go(inches of PMMA)	Calculated Pressure Input(Kbar)
Tritonal (80/20)	6/7 (Endplates)	14-18
Tritonal (70/30)	6/7 (Endplates)	14-18
TNT	6/7 (Endplates)	14-18
PBX-9502(7 inches x 10 inches charge)	4/5 (No endplates)	55-60
PBX-9503(7 inches x 10 inches charge)	7/8 (No endplates)	35-45
AFX-1100 (TNT/wax/Al-66/16/18)	2/3 (Endplates)	42-65
AFX-1100	6/7 (No endplates)	45-50
AFX-900		
PE/Al/RDX/NQ-16/17/18/49	7/8 (No endplates)	35-45
16/17/20/47	7/8 (No endplates)	35-45
16/17/18/49	6/7 (No endplates)	45-50

CASEWALL FRAGMENT VELOCITIES

The 8-inch-diameter cans used in the gap tests can also provide a valuable initial look at explosive performance. The metal driving capability of explosive formulations may be determined by positioning piezoelectric pins radially about detonating charges to measure casewall fragment velocities (Figure 8).

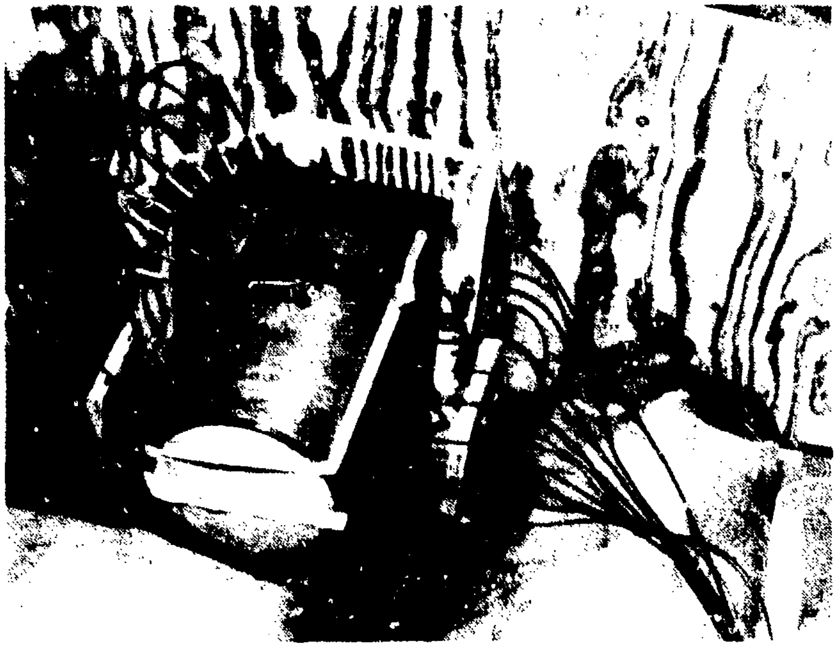


Figure 8. Gap Test with Radial Pin Array to Measure Casewall Fragment Velocity.

A blast shield is placed around the charge of interest between the point of initiation and the radial pin array. This shield deflects the axial wave long enough for the desired measurements from the radial, fragment producing wave to be obtained.

The radial pin array should be positioned around the experimental charge at a point where steady state detonation is achieved--a least one-fourth of the way down the charge of interest. One pin should be placed on the exterior surface of the casewall to define time zero. Pins should subsequently be spaced radially at least every 0.1R inches (every 0.4 inches for 8.0-inch diameter charges, R=4) out to about three inches from the casewall. Attempts to record casewall velocities beyond four inches from its original position have generally proven futile in the 16-in.-long cans. It appears that one of two events occur as the fragments travel beyond this radius. Either (1) the axial wave deflected by the blast shield catches up with the radial fragments, driving the shield through the pin array or (2) the radial shock front catches up with the fragments, interfering with the desired measurements. Regardless of the source of difficulty, reasonable velocity measurements are obtained in the prescribed diameter.

Once the average terminal casewall velocity has been determined for a particular explosive, its Gurney number may be determined from the equation:

$$\sqrt{2E} = \frac{V}{\sqrt{\frac{C/M}{1+C/2M}}}$$

where:

$\sqrt{2E}$= Empirical Gurney Constant (having dimensions of V)
V= Terminal Fragment Velocity
C/M= Ratio of explosive weight to case weight

The ratio C/M may be determined from

$$C/M = \frac{r_1^2 \quad \rho\,\text{exp}}{(r_2^2 - r_1^2)\,\rho\,\text{case}}$$

where:

r_1= radius of explosive charge = inner radius of casing
r_2= outer radius of casing
ρexp= calculated density of explosive charge
ρcase= density of case material

Calculated Gurney numbers may then be used to rate the explosive performance of IHE candidates against other known explosives and among themselves. Gurney numbers calculated from measurements obtained in the manner described are shown in Table IV.

TABLE IV. GURNEY NUMBERS CALCULATED FROM CASEWALL FRAGMENT VELOCITY MEASUREMENTS IN 8-INCH-DIAMETER CANS

Explosive	Vavg (km/sec)	M	$\sqrt{2E}$
AFX-900-P4(22) (PE/NQ/RDX/AL-16/17/22/45	1.31	32.5	2.56
AFX-900-P4(20) (PE/NQ/RDX/AL-16/17/20/47)	1.13	34.8	2.15
AFX-900-P4(18) (PE/NQ/RDX/AL-16/17/18/49)	1.01	32.2	1.99
Comp B (60/40)	1.59	18.4	2.95
Comp B, Grade A			2.99[5]
Comp B			2.71[6]
TNT			2.54[5]
Tritonal (80/20)			2.32[6]

INITIABILITY

After an explosive formulation has demonstrated an acceptable level of insensitivity to shock inputs in the 8-inch gap tests, initiability studies are conducted. Unquestionably, the goal of the Armament Laboratory's development efforts is to develop an explosive which can survive the adverse environments posed by the five IHE qualifications criteria. However, such an explosive is not serviceable if it cannot be readily and reliably initiated.

Initiability for an explosive is a strong function of critical diameter--the larger the critical diameter for an explosive formulation, the more difficult it is to initiate. The IHE candidates presently under review by the Air Force have relatively small critical diameters (1.0-2.0 inches). Theoretically there exists an overlap between the IHE zone and the initiation zone for explosive formulations (see Figure 9). The challenge is to determine the size of this overlap, if in fact it does exist, and to tailor IHE candidates to perform in this crossover zone.

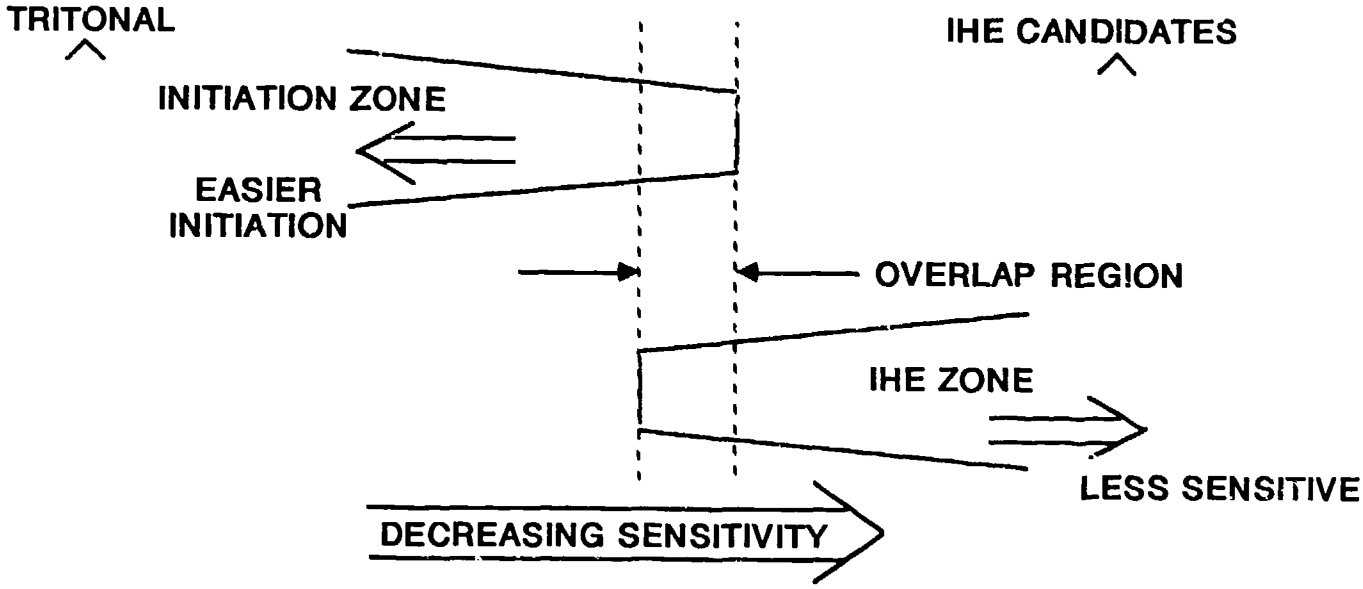


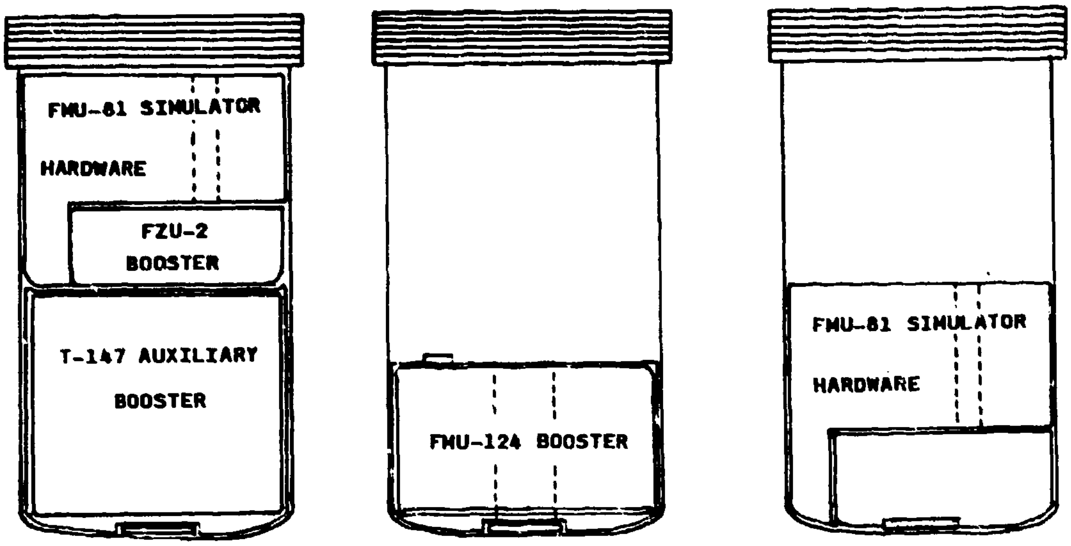
Figure 9. Initiation vs. Sensitivity--The Dilemma

It is desirable to develop an IHE which can be used in the existing hardware configuration with existing fuze/booster systems. Therefore, initiation studies begin by setting boosters from inventory fuzes against IHE candidates before proceeding to full scale testing. The booster tests are conducted in 8-inch-diameter cylinders which have standard fuzewell liners attached to the inside of the forward baseplate (see Figure 10). The items are positioned above RHA witness panels and instrumented with piezoelectric pins as in the gap test. The booster tests are conducted at -65°F to ensure reliability of the initiation system in extreme temperature conditions.

Figure 10. Booster Test Cylinder (FZU-2 and T-147 Booster Train Shown)

The boosters are inserted into the fuzewells in the configurations shown in Figure 11.

The 124g tetryl booster from the FMU-124 is tried first. The felt pad and heavy aluminum plating in the bottom of this fuze generate a radial impulse from its booster. This forces the reaction in the candidate explosive to "turn-the-corner" or transfer the radial wave into an axial wave. This corner turning process is not easily achieved by secondary explosives with large critical diameters.



TETRYL (303 GMS)
+
TETRYL (45 GMS)

TETRYL (125 GMS)

TETRYL (45 GMS)

Figure 11. Fuze/Booster Configurations

If the 124g tetryl booster is successful in initiating the main charge, the pie-shaped 45g tetryl FZU-2B tetryl booster from FMU-81 is tested. However, if the booster from the FMU-124 is not successful in initiating the candidate IHE, the 303g tetryl (T-147) booster from the M-905 fuze is tested. The FZU-2B is used to light the T-147 as illustrated.

If success is not achieved in this configuration, the type of impulse needed to initiate the IHE candidiate under evaluation requires a supplemental booster. The challenge is presented graphically in Figure 12.

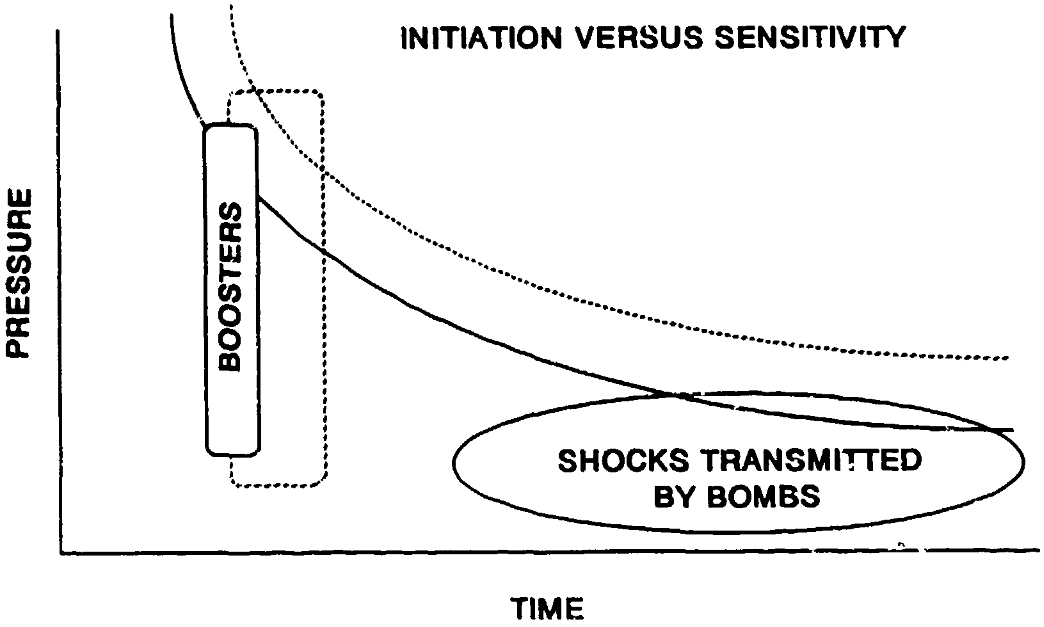


Figure 12. The Role of Impulse in the Initiation of Explosives.

The solid line on the pressure vs. time plot represents the $P^2\tau$ curve for typical explosives such as tritonal. The dotted line shows a $P^2\tau$ curve for IHE candidates. As is shown, the pressure impulse seen by a nearest-neighbor acceptor item in a sympathetic detonation environment is relatively low in terms of peak pressure but is long in duration. On the other hand, the pressure impulse from typical boosters is short in duration but has a relatively large peak pressure. As is illustrated, promising IHE candidates can escape the low pressure, long duration impulses from nearby detonations without propagating the reaction. However, since they are so insensitive, they may not be readily initiated by the peak pressures from existing boosters. The concept of the auxiliary booster is to increase the pressure impulse from conventional boosters by increasing their peak pressure output. This is accomplished by utilizing a booster containing larger amounts of explosive or by substituting a higher energy explosive into existing fuzes. The former solution has been tested using a 1 lb prototype booster of PBX-9503 (see Figure 13). The main charge explosive was readily initiated at -65°F.

Figure 13. Prototype Auxiliary Booster for Reliable Initiation of IHE

SYMPATHETIC DETONATION

The sympathetic detonation or propagation test is designed to determine the response of general purpose (GP) bombs to the detonations of nearest-neighbor items. Ultimately, the items are tested for mass detonation in the storage and shipping configurations. For MK-82's, the shipping configuration consists of two pallets of three bombs each, stacked one on top of another and banded together. MK-84's are handled as single pallets of two bombs each (Figure 14). Pallets of bombs are generally stored side-by-side and end-to-end in earth-covered, concrete igloos.

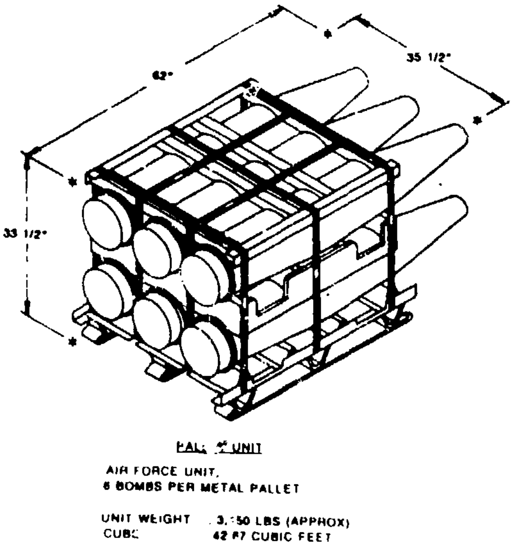


Figure 14a. Standard Handling Configuration for MK-82S

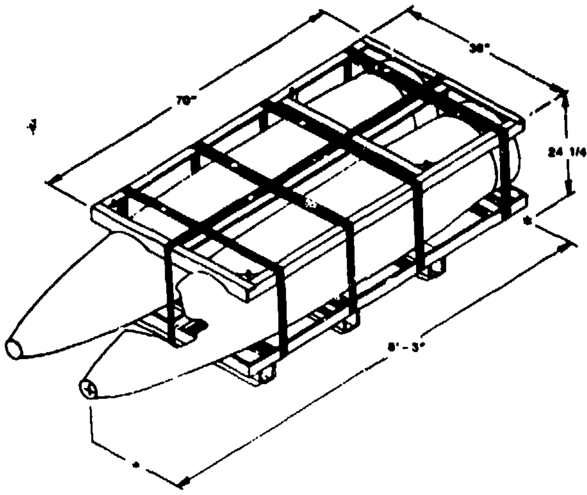


Figure 14b. Standard Handling Configuration for MK-84S

For testing, the items are initially placed side-by-side at the standard closest-point separations of 0.5 inches for MK-82's and 0.75 inches for MK-84's (see Figure 15). They are supported above 1.0-in.-thick rolled homogeneous armor (RHA) witness plate using cradles from standard wooden bomb pallets. Stacks of sandbags are placed along two edges of the armor witness panel to catch the radial fragments and to deflect the major test remnants upwards. The donor bomb is detonated remotely. Composition C-4 explosive is packed into the fuzewell and initiated using an RP-1 detonator or an RP-2 detonator with datasheet ® (Dupont).

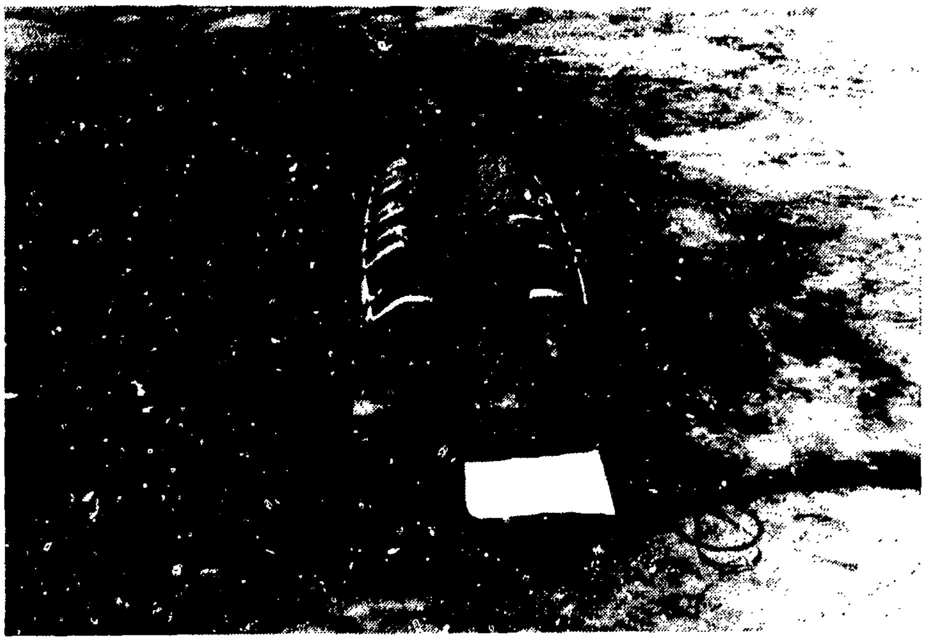


Figure 15. Set-up for the Sympathetic Detonation Test

The fuzewell may be plugged to eliminate the fire-producing jetting reaction resulting from their collapse. This arrangement helps prevent range fires without altering the conditions of the experiment.

When the test items are positioned in two dimensional arrays, fragment signatures on the witness panel and bomb case fragments generally provide sufficient evidence of the degree of reaction for the acceptor bombs (see (Figure 16). The witness panel is typically ripped into two pieces when detonations occur. Markings from the high velocity case fragments (similar to those observed from detonating items in the 8-inch-diameter gap test) scar the witness plate on either side of these fractures.

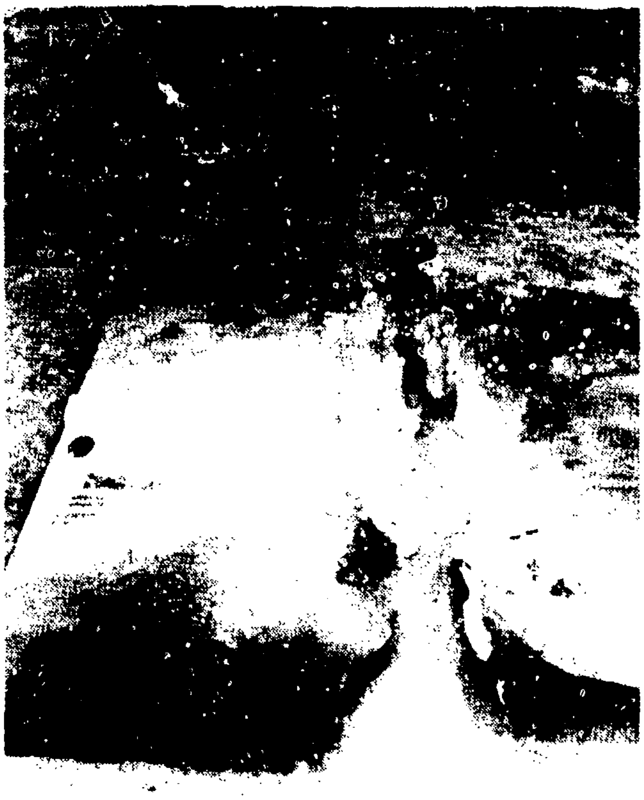


Figure 16. Witness Panel
The donor bomb was positioned directly above the crack.
The non-propagating acceptor bomb was positioned to the left of the donor.

The fragments recovered from detonating items are long and very thin (Figure 17). They show the effects of the very large stresses to which they are exposed during the expansion process and evidence the adiabatic shearing which occurs as the casewall finally breaks-up.

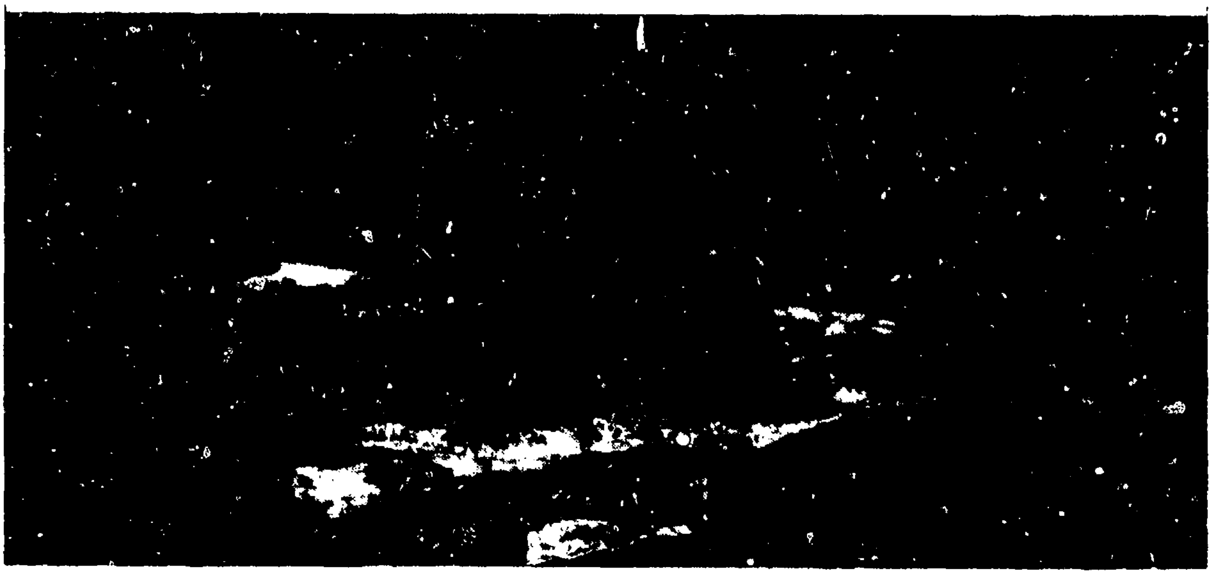


Figure 17. Fragments Typical of a Detonating Item in a Full Scale Sympathetic Detonation Test.

Fragments from acceptor bombs which do not detonate leave no markings on the witness panel; however, mild fractures are often observed directly beneath the original positions of these non-detonating items. These fractures do not result from the reaction of the acceptor bomb but from the high velocity fragments of the nearest neighbor donor bomb which are diverted into the witness panel by the acceptor before it is translated away from its original position.

Case remnants from non-detonating items are typically much larger than the fragments of detonated bombs. They are thicker and show no evidence of adiabatic shearing. The acceptor case remnants recovered are usually severely scarred from fragment impacts. Some post test acceptor pieces actually have portions of the donor bomb welded to them (see Figure 18).

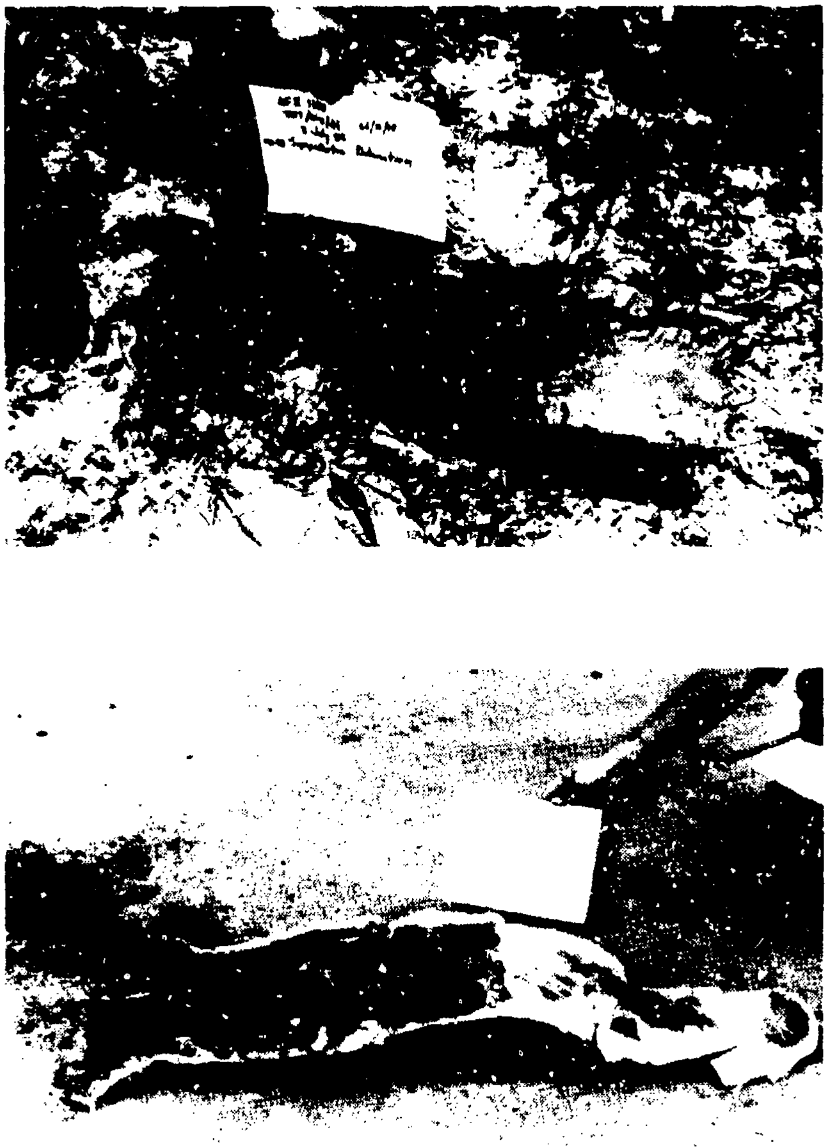


Figure 18. Typical fragments from non-detonating acceptor bombs in a full scale sympathetic detonation test.

Additionally, the recovery of any unreacted high explosive (HE) after the event is always a clear indication that at least one item in the array did not detonate.

Piezoelectric pins (Dynasen Inc., CA-11136) may be positioned along the casewall of the donor bomb to measure the detonation velocity of its explosive fill and provide additional evidence that a detonation did in fact occur. High speed film is used to monitor the event. Exposure rates of 1000, 8000, and 40,000 frames per second from several different angles and fields of view will usually provide adequate coverage.

Air blast pressure instrumentation may be used as desired to further characterize the events occurring in two-dimensional arrays. This data source becomes almost essential for meaningful analysis of reactions in three dimensional stacks. Witness plate markings from items in the upper rows of 3-D arrays are not a definitive as those from the bottom row or from 2-D arrays.

For 3-D arrays, it is recommended that baseline shots using inert acceptors or tritonal acceptors be conducted against the air blast pressure instrumentation prior to collecting data on IHE candidates. The air blast pressure data from subsequent tests may then be compared with the baseline measurements to determine if mass detonation occurred. All blast pressure data is acquired using the procedures prescribed in the Joint Munitions Effectivness Manual: Test Procedures for High Explosive Munitions. (Reference 7). Additionally, piezoelectric pins may be positioned radially about acceptor bombs to measure casewall fragment velocities. These velocities are then compared to measurements from baseline tests of detonating items of the same explosive fill to determine if propagation occurred.

Acceptor cases from the upper rows of 3-D stacks are often damaged to the degree of being indistinguishable or they are translated long distances and are not recoverable. Tool and die may be used to lightly label the test items in 3-D arrays prior to detonation. This will assist in reconstructing the event during post-test analysis. Fragment collection is accomplished from a visual search.

Sympathetic detonation can result from direct shock transmission or from fragment impact. Fragment impact can propagate a detonation either by shock initiation or by ignition of the explosive with subsequent deflagration detonation transition (DDT). Mechanical deformation of the bomb and its explosive can also result in ignition with subsequent DDT. For the classes of explosive under evaluation by the Air Force Armament Laboratory as IHE, direct shock initiation appears to be the predominant mode.

Several IHE candidates have been tested for sympathetic detonation at various separation distances to isolate the contributions of shock transmission from fragment impact (Table V).

TABLE V. MK-82 SYMPATHETIC DETONATION RESULTS FOR SEVERAL IHE CANDIDATES

Explosive	Number of Tests	Separation Distance	Results
AFX-1100 (TNT/Wax/AL-70/12/18)	1	0.5 inches	No propagation of detonation
AFX-1100-II (TNT/Wax/Al-66/16/18)	2	0.5 inches	No propagation of detonation
AFX-1100-II	1	5.0 inches	No propagation of detonation
AFX-1100-II	1	10.0 ft	No reaction (severe fragment damage to casewall)
AFX-900-P4(22) RDX/NQ/AL/Polyethylene 16/17/22/45	1	0.5 inches	No propagation of detonation
AFX-900-P4(18) RDX/NQ/AL/Polyethylene 16/17/18/49	1	0.5 inches	No propagation of detonation

A very small separation distance (less than 1.0 inch), the pressure impulse felt by the acceptor bomb is quite large, but the donor casewall is still undergoing deformation and is not fully fragmented. Transmitted shocks are divergent due to the curvature of the bomb casewall combined with the fact that the donor bomb is initiated at the nose or tail. Therefore, at larger offsets the pressure impulse does not contribute as significantly to the propagation of detonation. Also, at larger separations, the energy from the donor fragments is distributed over such a large portion of the casewall that initiation of the contained explosive does not occur. Results indicate that worst case conditions exist at donor/acceptor separations of approximately one bomb radius. At this distance, the donor casewall has accelerated to maximum velocity upon impact with the acceptor. Also, peak pressure will be at a maximum in this region, but the total impulse will be lower since the donor casewall has expanded and is much thinner than it would be at closer spacings. The exact amplitude and duration of the pressure wave transmitted to the acceptor is not readily calculated since the Hugoniot values for the developmental explosives (unreacted and products) are not known. Effort is underway to develop predictive methods for donor/acceptor shock interactions using hydrodynamic codes such as HULL and TOODY. Regardless, fragment impact is not the primary source of detonation propagation for the IHE candidates presently under evaluation (Figure 19a-b).

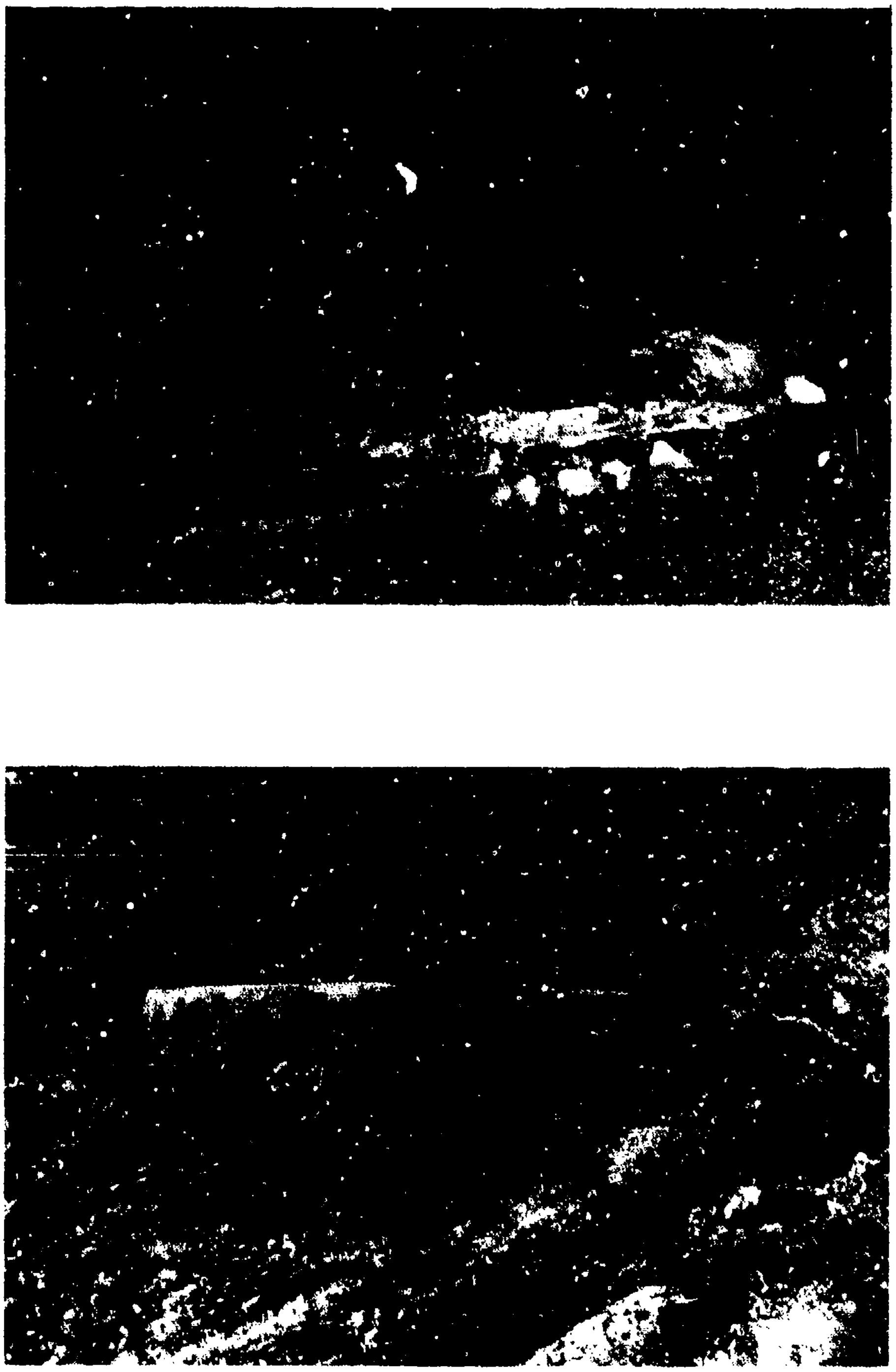


Figure 19. Sympathetic Detonation Remnants from Acceptor Bombs at Separation Distances of a) 5 inches and b) 10 ft from the donor bomb.

SLOW COOK OFF

The slow cook off represents the environment that a bomb could sense in storage of shipping if it was in a magazine adjacent to a fire. As the temperature rises, the rate of explosive decomposition is increased until self heating or spontaneous ignition occurs. This reaction, which involves essentially all of the contained explosive, most likely begins inside the explosive where the amount of self confinement determines the violence of the response.

In a slow cook off test, the item under evaluation is enclosed in an aluminum coffin-type oven (see Figure 20). It is supported inside the oven by a separate, steel, angle-iron stand. Exudation troughs are provided at the nose and tail of the bomb for the removal of any molten explosive which might exude from around the fuzewell liners. Additionally, the oven is equipped with ports to provide air circulation. Ducts from the ports feed to a recirculating blower which is protected behind a concrete block. The movement of the air maintains a uniform temperature throughout the oven airspace. Electrical heating tapes are wrapped around the exterior of the oven and insulation covers both the oven and the air ducts. Thermocouple wires are placed throughout the oven airspace. They are also attached to the inside of the oven wall and the bomb skin as well as inside the fuzewells and charging conduits to provide a temperature record throughout the experiment.

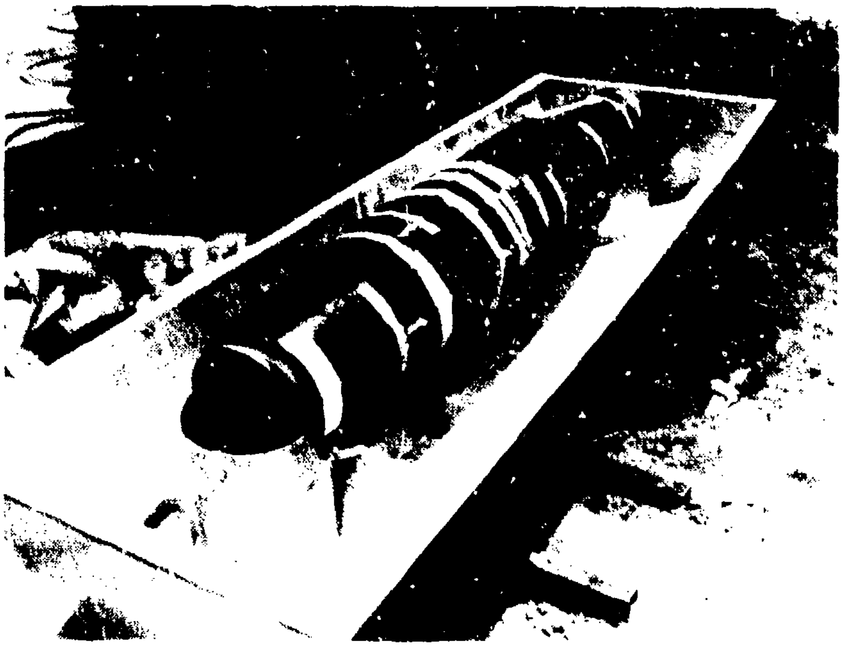


Figure 20a. The Slow Cook Off Oven

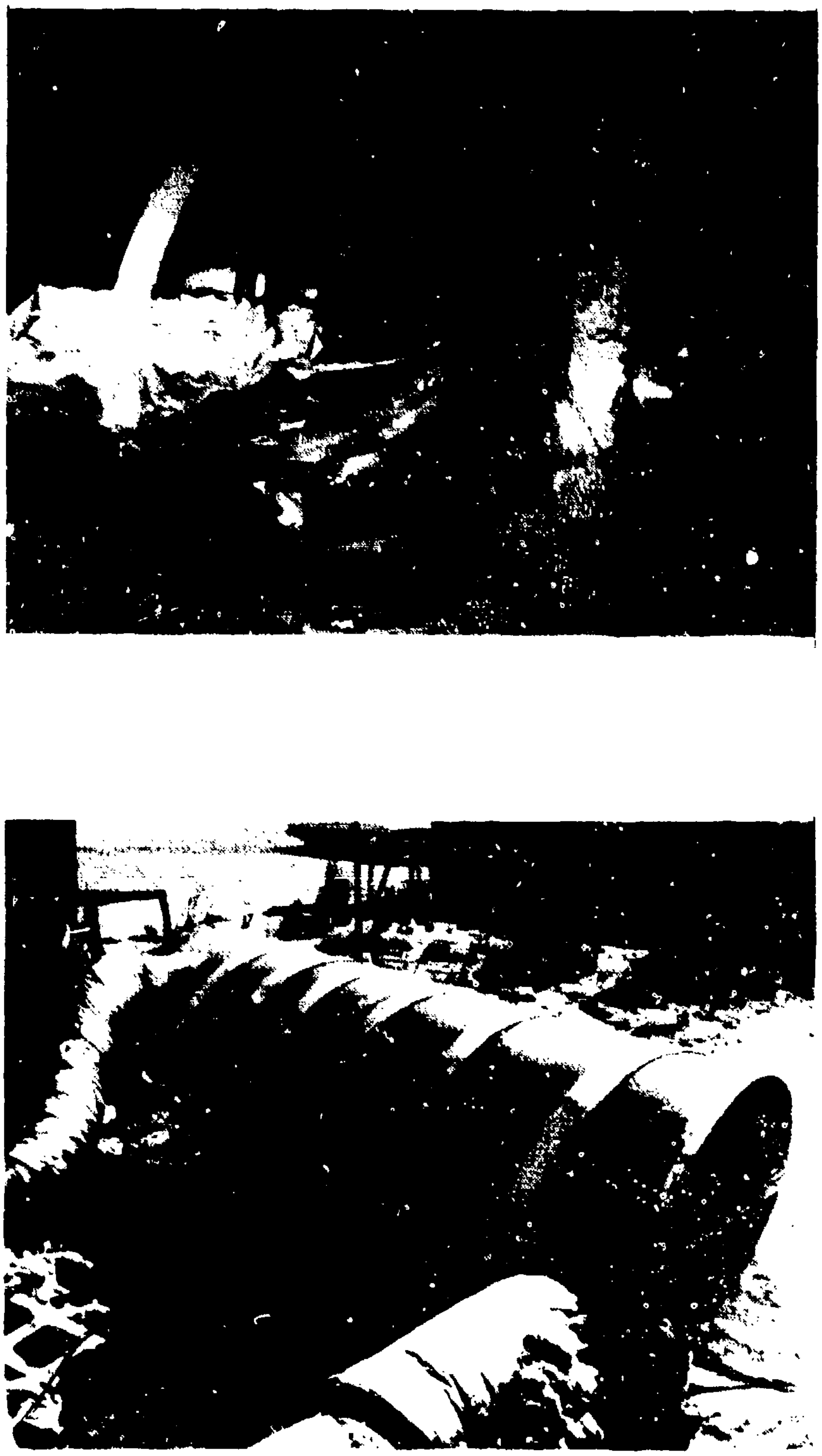


Figure 20b & 20c. The Slow Cook off Oven

Figure 20d. The Slow Cook off Oven

Since it is speculated that the slow cook off results in a gradual pressure build-up inside the bomb, it is desirable to monitor the internal bomb pressure to determine when mechanical failure occurs. Pressure measurements may be accomplished with a high temperature rated transducer-type gauge tapped through the bomb-skin.

During a slow cookoff, ambient conditions must be taken into consideration. The oven temperature should be raised to 20-30°C above the formulation melt temperature and these conditions maintained until a pseudoequilibrium is achieved between the bomb and the airspace. The bomb-fill temperature is monitored by tracking the profile measured inside the charging conduit. Pseudoequilibrium is achieved when the temperature vs. time curve for the airspace and the bomb fill become horizontally parallel. In full scale testing, this is a slow process involving the phase change of 150-200 lbs of explosive in MK-82s.

The heating process for the actual slow cookoff test is then initiated by presoaking the item at approximately 55.5°C below the expected reaction temperature as prescribed by DoD-STD-2105(NAVY) (Reference 8). Again, the bomb should be maintained at this temperature until pseudoequilibrium is achieved with the airspace.

Next, the average temperature of the airspace is increased at a rate of 3.3°C until reaction occurs. Temperature control may be accomplished manually or by using a feedback control loop. Trial runs on inert items should be attempted prior to live testing to establish confidence in the temperature control mechanisms.

Temperature readings should be recorded at least once per minute until the test item nears the predicted reaction temperature. At this point the recording rate should be increased to about one every ten seconds to provide a better sampling of the temperature profile.

Video monitoring should be used to record the event. Due to the length of testing, night lighting may be necessary and should be arranged prior to beginning the test. Once testing has started, no personnel should be allowed in the test arena until reaction of the item occurs or a system malfunction results in a no test and range safety personnel authorize entry.

Post test analysis is accomplished by reviewing the pressure and temperature profiles and viewing the test remnants and video recordings. If the item merely burns, it remains in tact in its initial position. Damage to the test fixtures results only from the heat and smoke of the fire (see Figure 21).

Figure 21. Post Test from a Slow Cook off Burn

If the item explodes, the test fixture will be consumed by the reaction and the bomb casing will break into small pieces. The pieces are thicker and heavier than those resulting from a detonation (see fig. 22). It is unlikely that any of the molten explosive will remain unreacted after a slow cookoff explosion.

Figure 22. Remnant from a Slow Cook off Explosion

A detonation in the slow cookoff is evidenced by small, highly sheared fragments and cratering as well as other severe damage around the test site. As mentioned previously, the slow cookoff test presents one of the major challenges to the Insensitive High Explosive development programs. Its applicability in terms of Air Force life cycle environments is currently under review by a DoD technical review panel.

SLED TESTS

The sled test required for Air Force qualification of an IHE is conducted to determine the sensitivity of the candidate formulations to high velocity impacts (1450 ft/sec) with reinforced concrete targets (Figure 23 a-b). This differs from the subsonic velocity sled test used on items to determine penetration effectiveness. Eglin AFB has a 2,000 ft dual rail sled track inclined at 0.6 percent. For general purpose bomb tests, the track is used as a monorail carrier sled. The item is secured to the carrier sled with two nylon straps. The rear fuzewell remains empty while a nose plug and nose support cup are used to reinforce the point of impact.

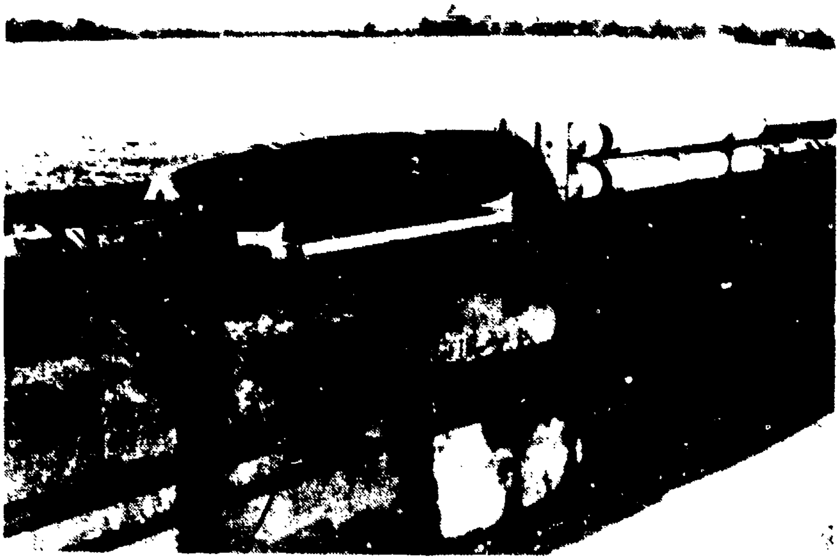


Figure 23. The a) Item and Sled Propulsion System and

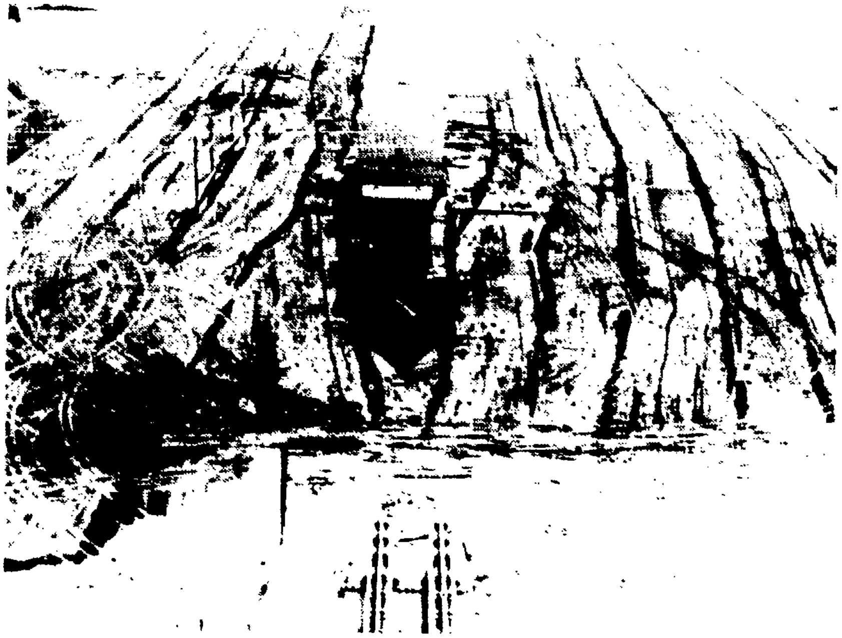


Figure 23. b) the 10 ft x 10 ft x 4 ft Reinforced Concrete Target

Six Zuni rocket motors are used to accelerate the pusher sled to the desired velocity. At the end of the rail, the item separates from the carrier sled and enters the center of the 10 ft x 10 ft x 4 ft steel reinforced concrete at zero abliquity. The exhausted rocket motors are deflected away from the target by a large diverter. High speed cameras (8000 frames/sec) monitor the impact event from several different angles.

Post test analysis is accomplished from viewing the high speed film and examining the test remnants, including case fragments, unreacted explosive and the remains of the concrete target. (Fig 24 a-d).

Figure 24. Sled Test Remnants for a) an IHE Candidate which did not react

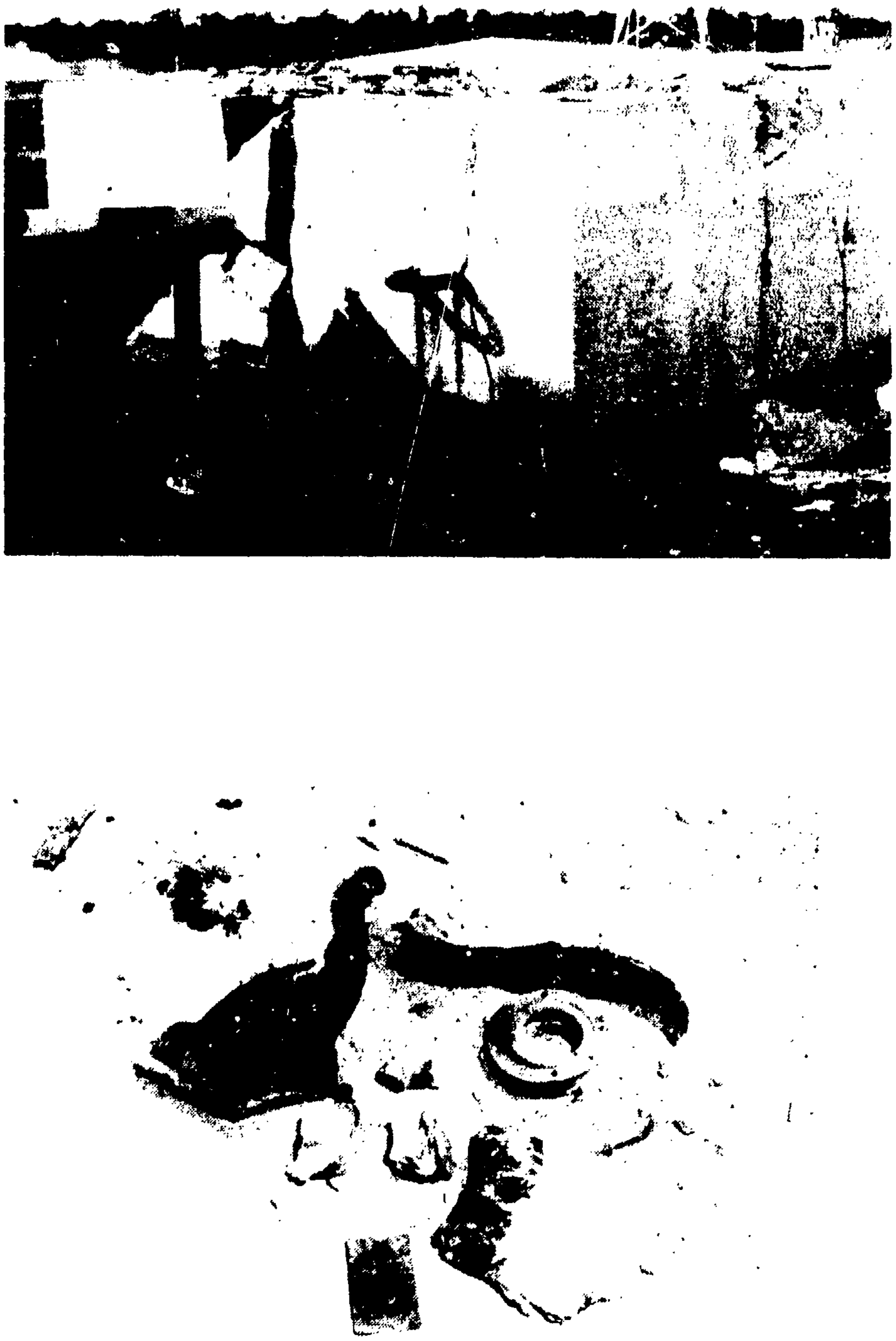


Figure 24. Sled Test Remnants for b) an IHE Candidate which did not react and c) Tritonal Which Exploded.

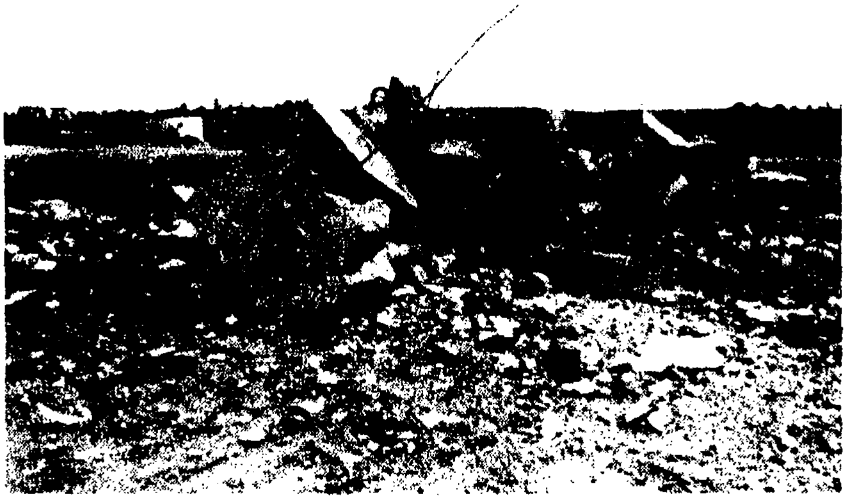


Figure 24. Sled Test Remnants for d) Tritonal Which Exploded

The applicability of the sled test for Air Force IHE candidates is also under scrutiny by a DoD technical review group.

BULLET IMPACT

DoD-STD-2105(Navy) (Reference 4) states that "the bullet impact test is designed to evaluate the response of major explosive subsystems to the kinetic energy transfer associated with the impact and penetration by a given energy source." For the U.S. Air Force, this energy source is a three round burst of .50 cal AP delivered at service velocity (app. 3000 fps) from a distance of 30-70 meters.

For testing, a single MK-82 or MK-84 filled with the candidate explosive is placed on a heavy wooden stand, 110 ft downrange from the projectile delivery source. The Air Force uses the M-2 machine gun (Figure 25).

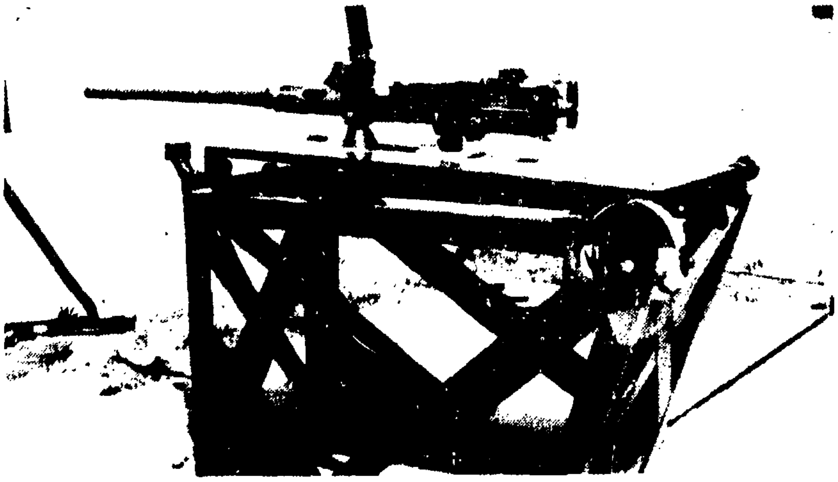


Figure 25. M-2 Machnie Gun used for Bullet Impact Testing

One may also use a set of three Mann barrels energized with a sequencer to deliver the desired three rounds and activated remotely using a solenoid switch. Before attempting to impact a live test item, several rounds are fired through velocity screens into a target located above the test stand. The gun is adjusted until the target is realiably penetrated in the region of interest and adequate velocity measurements are acquired. The velocity screens are then removed from the arena and a three round burst is fired at the target to determine the scatter pattern. Final adjustments are performed until a 3 to 4-inch-diameter pattern results from the multiple impacts.

The test item is then moved into position. The gun is loaded and the test rounds are fired. Identical tests items must be impacted in three separate orientations by three separate three round bursts:1) the baseplate 2) the centerpoint between the suspension lugs and 3) a point 10 inches in front of the forward suspension lug. High speed film (1000 frames/sec and 4000 frames/sec) is used to record the event from different angles. Video monitoring is used for safety purposes.

IHE candidate filled items may not appear to react upon impact; a waiting period of 30 minutes should be allowed to ensure hotspots which could lead to a delayed reaction, are quenched. If no reaction occurs, the same item may be impacted in three different orientations.

Post test analysis is accomplished from the high speed film records and item remnants. As just mentioned, IHE candidate filled items may not react appreciably. Slight smoking of the item may appear on the film records. If this is the scenerio, the item will remain essentially intact (see Figure 26 a-d).

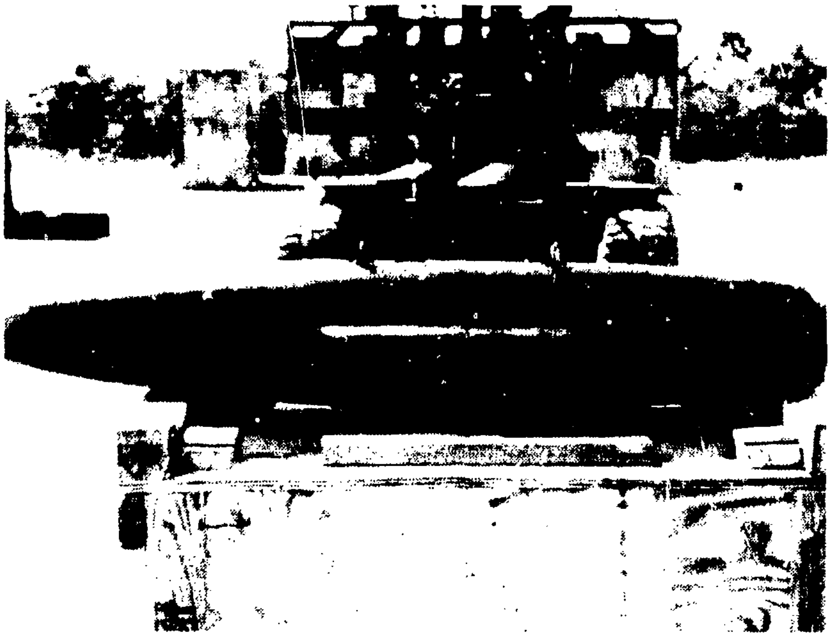


Figure 26. Nonreacting Item in Bullet Impact Test, a) Overall View

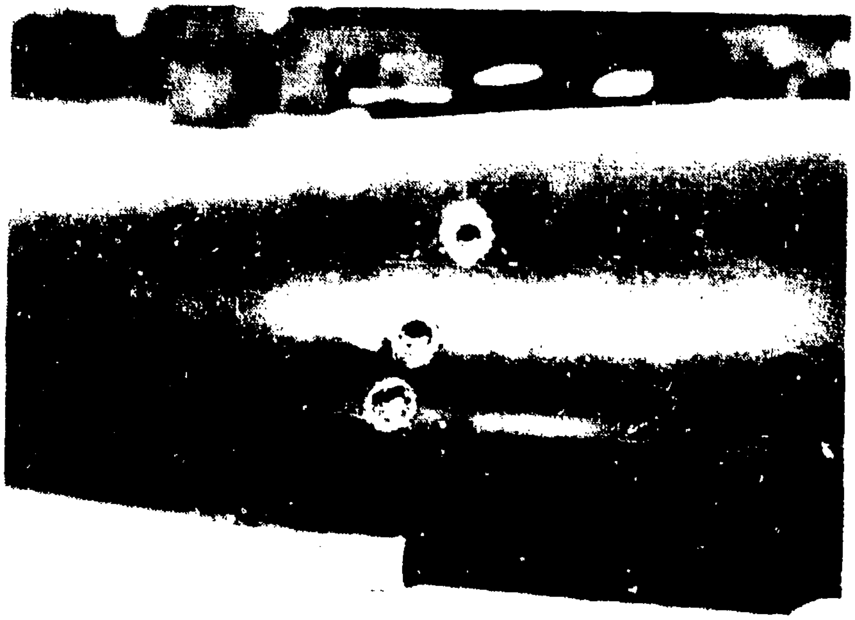


Figure 26. Nonreacting Item in a Bullet Impact, b) Closeup of Nose Impact

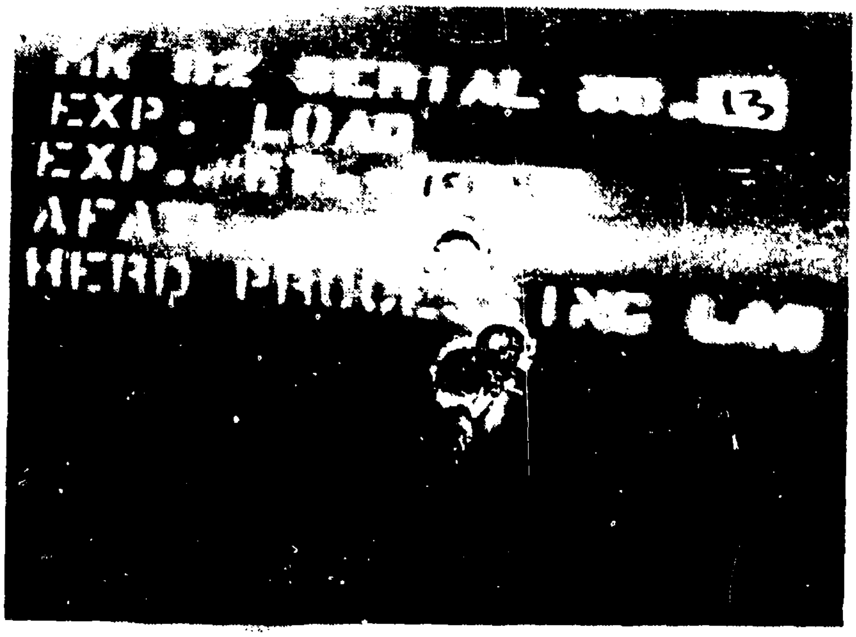


Figure 26. Nonreacting Item in a Bullet Impact Test, c) Closeup of Center Impact

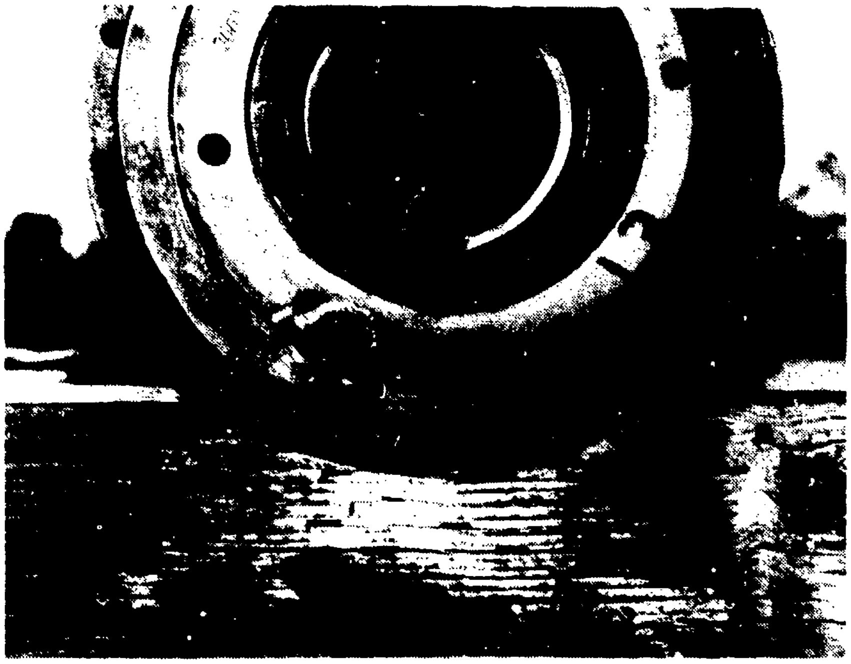


Figure 26. Nonreacting Item in a Bullet Impact Test, d) Closeup of Baseplate Impact

The item must be handled carefully and disposed of using the proper procedures. However, the item is likely to undergo one of the following reactions:

If the item explodes, a bright fireball will appear on the film and the bomb will break-up into large, heavy pieces. Unreacted explosive will be scattered about the arena. This sort of reaction, although extremely violent, is permitted by the IHE criteria. It is interesting to note that in the tests for which an explosion has occurred, the large fragment resulting from the casewall where the ammunition impacted contains only one hole, indicating clearly that the first round of ammunition produced the reaction before the subsequent rounds reached the item (Figure 27).

Figure 27. Post Test Remnants of an Exploding Item in the Bullet Impact Test. The item was filled with tritonal.

A detonation is evidenced by a larger, brighter fireball on the film records. Small, thin fragments which show the classic signs of stress and adiabatic shearing are normally recovered. Ordinarily, all of the explosive in a bomb is consumed during a detonation.

BONFIRE (FAST COOK OFF)

It is difficult to predict all of the hazards to which a general purpose bomb will be subjected during its life cycle. It is speculated that at some point, either in storage or shipping some items will be exposed to a woodfire. The survivability of bombs filled with insensitive high explosive (IHE) candidates in such a fire is determined in the bonfire test or fast cookoff "to ascertain the effect of fire external to the items or packages and, in the event that the fire causes deflagration, detonation, or explosion, to ascertain the violence and extent of propagation and the external hazard," (Reference 9).

In a fast cook off, thermal decompositon of the explosive most likely begins at the interface between the test item and the explosive, initiated by thermal hot spots. Recall, this is different from the slow cook off in which esstentially all of the explosive is uniformly raised to reaction temperature.

During development testing, a single bomb is steel banded to a stand about 1 meter above the ground. Dry 1 inch x 4 inch lumber is stacked under and around the test item to give at least one half meter of wood in all directions (Figure 28 a-b). The wood is drenched with approximately 15 gallons of kerosene or diesel fuel and ignited by two incendiary (thermite) hand grenades. The grenades are situated to prevent reaction with the test item and are ignited with a time delay fuze.

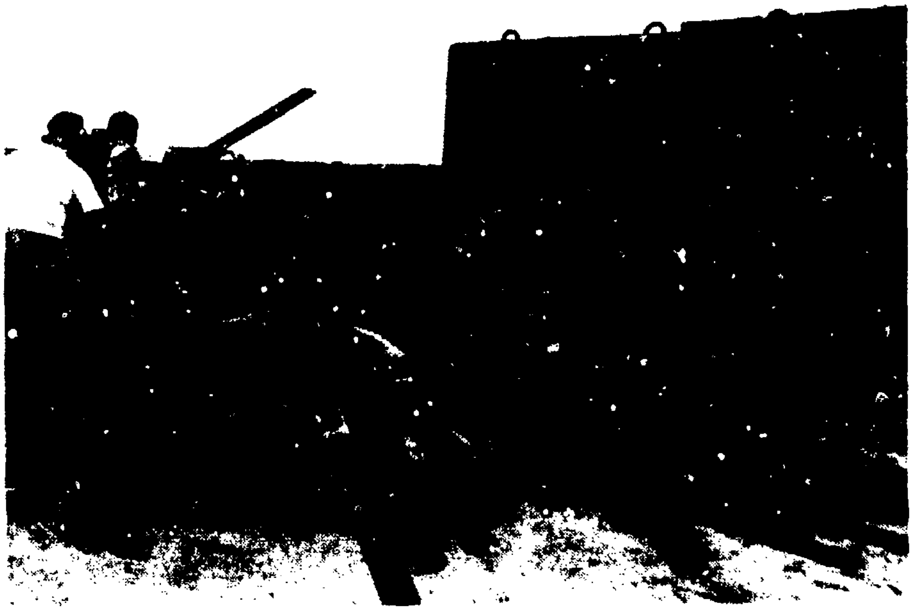


Figure 28. Buildup for the Wood Bonfire Test. Lumber surrounds the test item to give at least one meter of wood in all directions.

Figure 28. Buildup for the Wood Bonfire Test. Lumber surrounds the test item to give at least one meter of wood in all directions.

Closed circuit television and 30 frames/sec (real time) film is used to monitor the event. A minimum waiting period of 12 hours is required after reaction of the item before it may be approached for post test analysis. The analysis generally consists of viewing the case remnants and unreacted explosive (if any) to determine the degree of reaction (Figure 29).

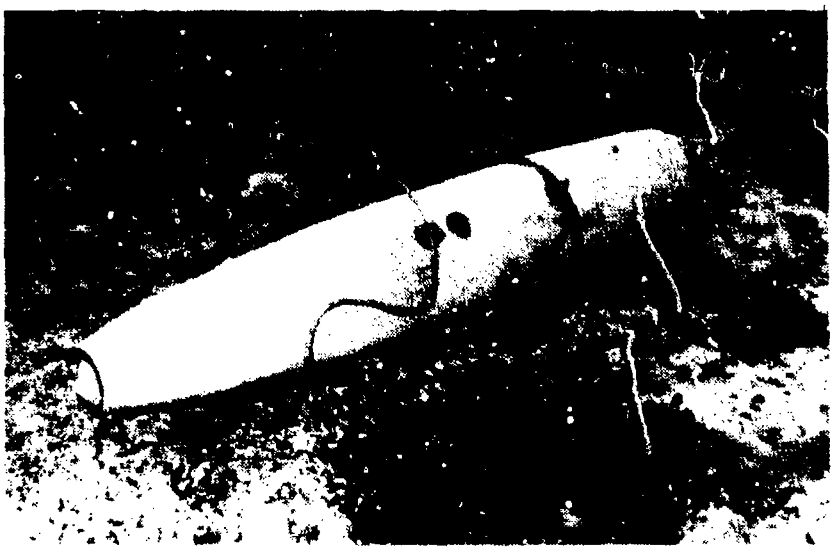


Figure 29. Bonfire Remnants for one of the Armament Laboratory's IHE candidates--a burn.

FUEL FIRE TEST

The fuel fire fast cook off does not presently exist as one of the Air Force insensitive high explosive qualification criteria. However, this test is currently prescribed for the Navy by DoD-STD-2105(Navy) (Reference 4). It has been proposed that upon establishing DoD Technical Requirements for Insensitive Munitions, the fuel fire test be required by all services in lieu of the wood bonfire test. The Air Force therefore tests its IHE candidates in fuel fires in accordance with MIL-STD-1648A(AS) (Reference 10).

Experience suggests that both the fuel fire test and the bonfire test are fast cookoffs. The principle difference being the peak temperature and the rise times to this peak temperature. The fuel fire generally reaches temperatures as high as 1800-2000°F in a matter of a few seconds. The wood bonfire, on the other hand, builds slowly over a period of several minutes to a maximum temperature of approximately 1000-1200°F. The fuel fire gives more reproducible results, because the time to cookoff is less dependent on meteorological efforts.

The test consists of suspending an item of height of three feet above the surface of 1200 gallons of JP-4 or JP-5 fuel. A steel I-beam with lug attachments supports the item. The fuel is contained in a steel pan (Figure 30) or a film lined earth test pan. Thermocouples are positioned at the same height as the item, approximately four inches from each side. The fuel is ignited using incendiary hand grenades with time delay fuzes.

Figure 30. The Configuration for the Fuel Fire Test

The temperature profile is monitored and recorded at least once every second. An An average flame temperature of 1600°F during the course of the test constitutes a valid evaluation. Closed circuit television or color motion picture film provides a video record of the event.

Post test analysis is accomplished by viewing the case remnants and unreacted explosive (if any) to determine the degree of reaction.

ARENA TEST

The Air Force Armament Laboratory intends to develop an Insensitive High Explosive with a performance level similar to that of existing bomb fills (i.e. tritonal). Warhead blast and fragmentation effectiveness parameters are measured in the arena test.

In this test, the item being evaluated is detonated at the centerpoint of a 90 degree array of 4-ft-thick stacked fiberboard. Behind the fiberboard are 4 ft thick stacks of plywood. The 16-ft-tall bundles are positioned at a prescribed radius from the item and are supported on special steel stands. Additionally, velocity screens are placed in front of the fiberboard. A 90-degree array of 16-inch-thick mild steel flash panels are positioned adjacent to the fiberboard bundles (Figure 31). Combined, these fixtures provide fragment velocity, weight, size, and distribution data.

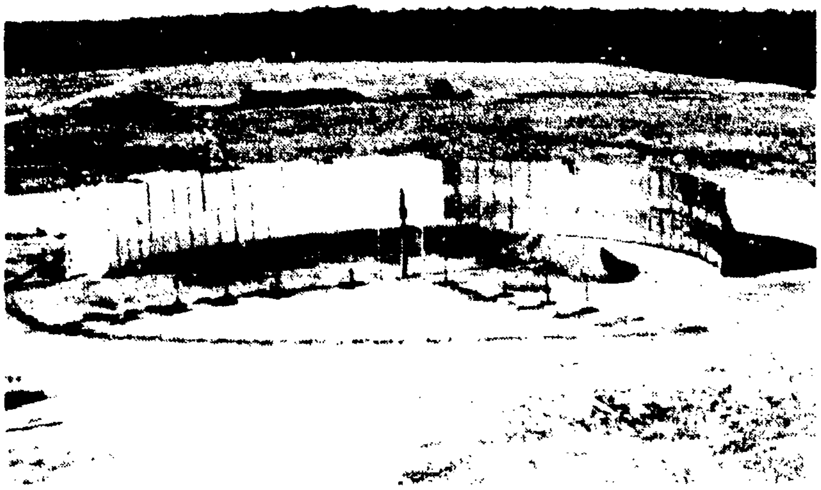


Figure 31. The Arena Performance Test (a) Before

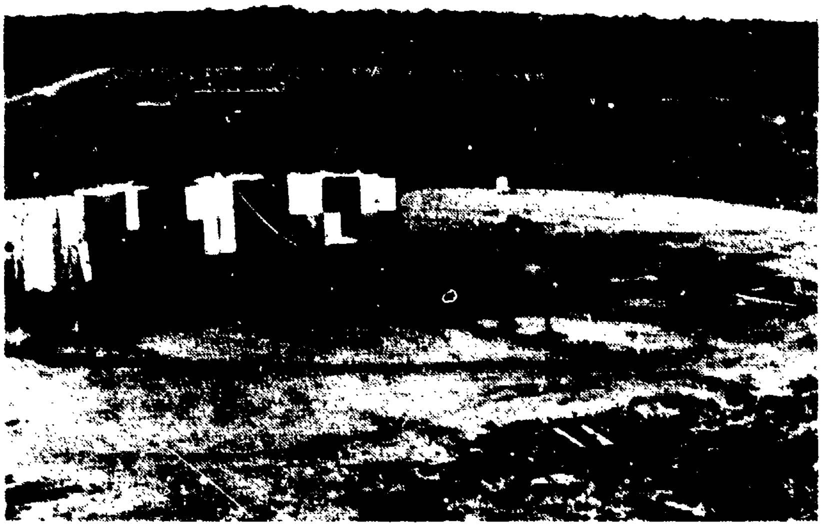


Figure 31. The Arena Performance Test (b) After

As the metal fragments reach the 4 by 8 ft aluminum coated velocity screens, electrical impulses are generated. The impulses are recorded to be used in calculating the fragment velocities. After penetrating the velocity panels, the fragments are trapped in the fiberboard and plywood bundles. As they are recovered, the X-Y-Z coordinates of each fragment is recorded along with its weight and size. Additional fragment distribution data (X-Y coordinates) are provided by the flash panels.

Obviously, only a small portion of the total bomb skin is accounted for in this test. When detonated in a vertical configuration, a large portion of the fragments from azimuthal zones (see Figure 32), are recovered from a small set of polar zones. The particular polar zones recovered are a function of item height. Several shots must be performed to adequately sample the major fragment producing polar zones. Conversely, in a horizontal test the entire set of polar zone fragments may be sampled from a very small number of azimuthal zones. Meaningful nose and tail fragmentation data may only be obtained from horizontal arena tests.

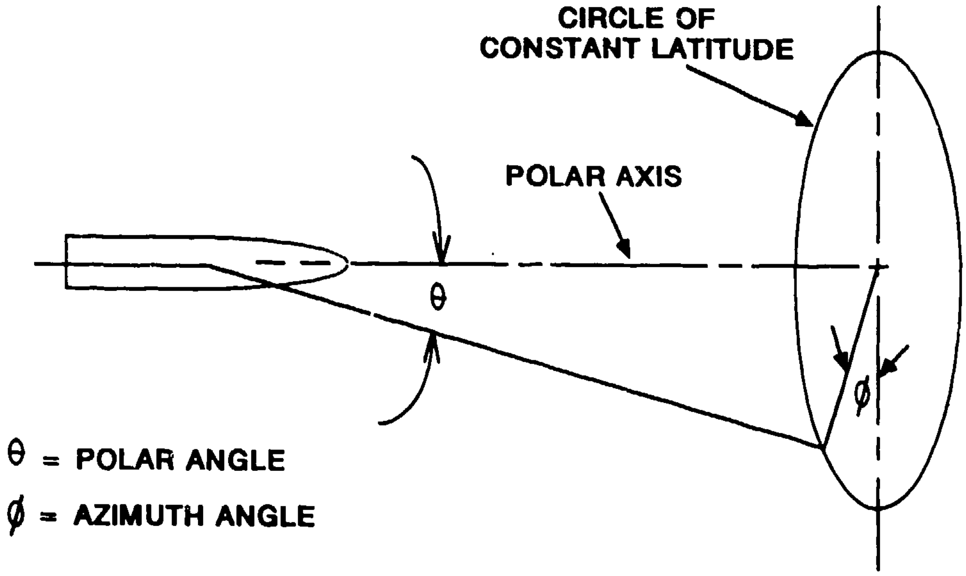


Figure 32. Polar and azimuth angles

In addition to the fragmentation data, air blast pressures are measured. Two gauge lines, 90 degrees apart (see Figure 33), are used to assure against loss of data.

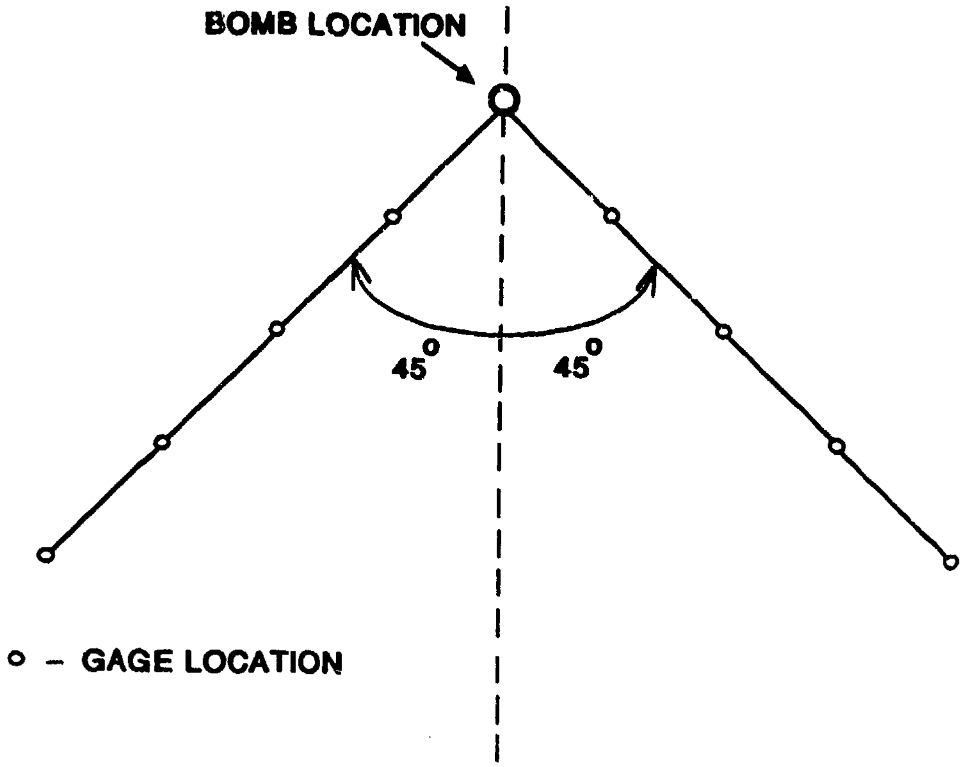


Figure 33. Typical Gauge Layout

The gauges are positioned on the side of the bomb opposite of the fiberboard bundles and flash panels at 10 ft radial spacings from 15 ft out to 65 ft. High speed film (8K frames/sec) from several different angles is used to record the event. Free air blast data may be obtained by positioning the gauges in the mach stem region at the same height as the detonating item. Eventually, the fragmentation data and blast pressure data are combined to calculate the probability of kill (Pk) for a GP bomb filled with the particular explosive candidate against a variety of targets.

RESULTS AND CONCLUSIONS

The challenge of developing an Insensitive High Explosive that is readily initiable and which provides acceptable levels of performance is formidable. Progress toward meeting this challenge is being accomplished with melt-cast explosive systems.

AFX-1100 is a wax, TNT, aluminum system. This explosive has passed each of the five IHE qualification tests in MK-82s at least once during its development cycle. Complete suppression of sympathetic detonation has been achieved only in two dimensional arrays. The additional confinement which exists in three dimensional stacks causes total elimination of propagation to be very difficult in GP bomb storage and shipping configurations. AFX-1100 has passed the slow cookff twice by venting and burning mildly; however, on three other occasions AFX-1100 has exploded during this test. The role of confinement in slow cook off reaction severity is being studied. It is speculated that the violence of the reaction from this test could be controlled by designing a realiable means of mechanical failure into the bomb hardware. The feasibility of tear away fuzewell liners or melt out plugs to relieve pressure is being explored. Additionally, performance parameters for AFX-1100 are being evaluated from data collected in this arena test.

AFX-900 is an RDX, nitroguanidine, aluminum melt cast system with a low melting polyethylene binder. It has demonstrated acceptable levels of shock sensitivity and is initiable at -65°F with a 1.1 lb PBX-9503 prototype booster. AFX-900 has survived the MK-82 sympathetic detonation test with a formulation containing 16% polyethylene binder and as much as 22% RDX.

Variations of AFX-1100 and AFX-900 are also undergoing evaluation. These simultaneous efforts are designed to bring about an effective IHE system in an expedited manner.

The payoff is big. The introduction of IHE into the inventory will instantaneously increase munitions storage capacity, dramatically enhancing operational readiness. The evaluation techniques used in this development effort are designed to ensure that munitions systems can survive the maximum credible event without posing a hazard to our own troops, allies, or the civilian community.

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TWENTY-SECOND DOD EXPLOSIVES SAFETY SEMINAR
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GUN PROPELLANTS FOR LOW VULNERABILITY AMMUNITIONS

BY D. DEGAND, J. GOLIGER and F.X. BOISSEAU *

INTRODUCTION

Most of gun propellants, in use today, contain nitrate ester which determine their explosive behavior with regards to intentional aggressions.

For the large caliber weapon propellants, violent damages can be observed if one of the rounds is accidentally set off.

For the infantry weapon propellants, the thermal behavior is considered as the problem (short and long cook-off).

These problems are being corrected by using more thermoresistant and less sensitive energetic material.

The French LOVA gun propellant, RDX dispersed in an inert binder (HTPB binder, for example), is one of possible candidate solutions which is presented in this paper.

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I - VULNERABILITY TESTS ON GUNPROPELLANTS CURRENTLY USED IN FRANCE

The vulnerability tests allow to have some information on the explosive behavior of the gun propellants submitted to deliberate aggressions such as:

- bullets
- shaped charges
- crushing
- explosive shocks
- thermal aggressions

The explosive behavior consists of :

- the blast effects
- the thermal effects
- the projections effects

Three levels of size for the samples are possible :

- the laboratory tests (up to 3 kg of explosive material)
- the model tests (up to 20 - 30 kg of explosive material)
- the true size tests on ammunitions

The tables 1 present the main French laboratory tests.

The table 2 and figure 1 present the main French model tests.

Some interesting true size tests are reminded at the end of this paragraph.

TABLE 1 - FRENCH LABORATORY TESTS

NAME OF THE TEST	AGGRESSION	SAMPLE	OBSERVED VALUE	POSSIBLE OBJECTIVE
PRELIMINARY TESTS D S C, A T D	Thermal	Some mg	Temperature	
FRICTION SENSITIVITY SIMILAR TO UN TEST 3 (b) (i)	Loads from 5 to 360 N between two rugose plates	Lamella thickness 0.5 mm	Load for decomposition and explosion	F > 80 N
DETONABILITY TESTS (1)	Calibrated shock wave	Sloped set (5°-600 mm x 100 mm) of gun propellant	Critical thickness "e" of detonation	e > 20 mm
UN 5 b (i) (2)	Ignition by hot wire of encased product	Filled into a steel closed tube ID40.2mm length 1.200 m	Length before detonation "LBD"	LBD >1,200 mm
GAP TEST UN 1 - a (iv)	Intense shock 3 x 10^4 MPa	Filled into a steel tube ID40 mm - length 200 mm between 2 boosters and an inert barrier	Thickness of cellulose acetate preventing the propagation of detonation in gun propellant	<45.6 mm

TABLE 1 (BIS) - FRENCH LABORATORY TESTS

NAME OF THE TEST	AGGRESSION	SAMPLE	OBSERVED VALUE	POSSIBLE OBJECTIVE
SHAPED CHARGE TEST	100 KJ shaped charge through a steel plate, 65 mm thickness	Filled into a cardboard tube ID95 mm length 350 mm	Reaction	no detonation
30 KG FALL HAMMER TEST UN 3 - a (iv)	Impact energy = from 7.5 to 1200 J in steps of 75 J	Filled into a steel tray, 8 mm deep, 50 mm wide and 150 mm long	height above which there is no reaction	$H \geqslant 0.75$ m
CRITICAL HEIGHT OF EXPLOSION	Ignition by hot wire of encased product	Filled into a seamless steel tube closed at one end ID 82.5 mm	Height of sample for which the substance pass from deflagration to detonation	$H \geqslant 1$ m
HOT BALL TEST	Conductive ignition by hot fragment (temperature from 200 to 800°C ; mass from 0.13 to 6 grams)	Filled into 20 x 50 mm glass vial	Total ignition temperature for a determined ball mass	-
IGNITABILITY TESTS (1)	Laser CO2 (80 to 300 W/cm^2)	One grain of gun propellant	Time for ignition with reference materials	-
(2)	Flame (propane gas-air)	70 g in closed vessel of 3 liters		

TABLE 2

MAIN FRENCH TESTS ON MODELS USED IN VULNERABILITY PROGRAMS

NAME OF THE TEST	AGGRESSION	SAMPLE AND CASING	CRITERIA AND OBSERVATION
BULLET IMPACT	Unique impact by a AP bullet of 12.7 mm. Velocity from 400 to 1200m/s by steps of 200 m/s	Volume of gun propellant = 3 liters Casing : steel Thickness 3 mm ID = 90 mm L = 309 mm It is a 90 mm cartridge case Closed by a 2 kg cannon ball (cylindrical) See figure 1 hereafter	There shall be no detonation -- The state of the casing is examined after each test -- The reaction is filmed

CRUSHING TEST	Unique impact by a 8 kg bullet, hitting the model at 65 m/s
	Bullet = Ø 81 mm
	h = 210 mm, steel		

FIRE TEST	External fire of 45 liters of fuel		
SHAPED CHARGE TEST	Unique impact by a 120 kJ shaped charge through a steel plate, 200 mm thickness		
SLOW COOK-OFF	A gradually increasing air temperature at 5°C/min		

The same casing is used towards different aggressions.

DESIGN OF THE MODEL FOR LOVA GUNPROPELLANT

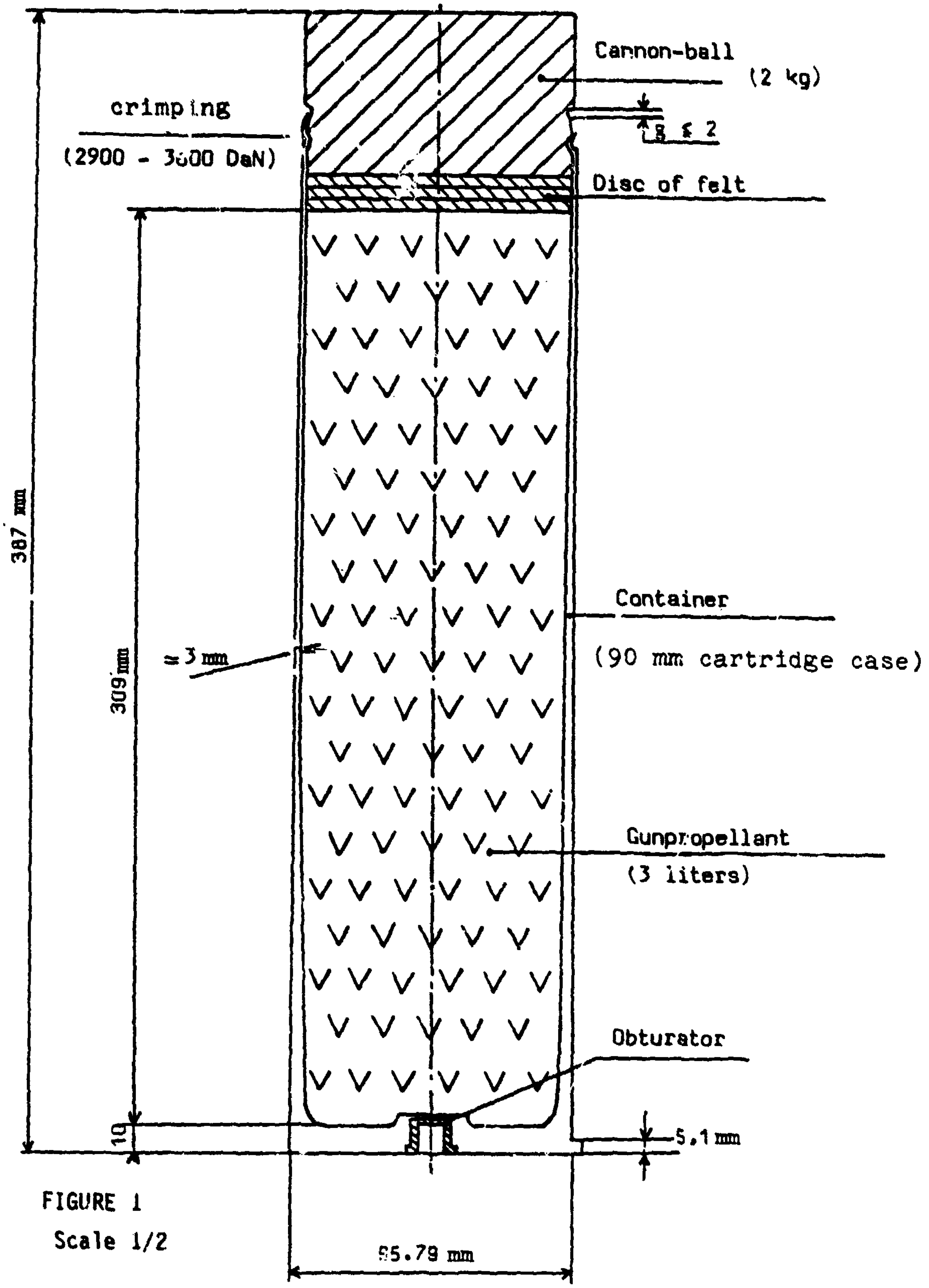


FIGURE 1
Scale 1/2

TRUE SIZE TESTING

Of particular interest are the tests on **packages** (the complete product consisting of the packaging and the ammunitions, or the gunpropellants).

Packages can be submitted :

- to fire (see U N test 6c)
- to bullet
- to shaped charge

Blast, projection, thermal flux must be recorded or collected if one wants to have detailed results.

II - EXPLOSIVE BEHAVIOR AND RESULTS ON 3 GUNPROPELLANTS

It must be reminded that the level of vulnerability of a weapon system is a characteristic of the total system (including the carrier).

In order to lower this level, and after reduction of the detectability and hittability of the weapon system, it is admitted that there are three types of solution.

<u>TYPE A</u> : Use a better protection to the munition (Armor, Kevlar sheets,...)

<u>TYPE B</u> : Redesign the casing of energetic materials ; for example fragilization of the outside casing to let the hot gases, go out, in case of ignition

<u>TYPE C</u> :Redesign the munition, and use less sensitive gunpropellants.

It is admitted that the use of less sensitive gun propellants improves the response of the weapon system. This paper is devoted to the influence of a change of the gun propellant.

Usually [illegible] gunpropellants in packagings detonate after an attack by a [illegible] charge, when they are unprotected.

Finer gunpropellants can detonate after an initiation by 50 to 100 g of high explosive.

TESTED GUNPROPELLANTS

Three gunpropellants were tested

1° - Gunpropellant type B 19 T - 1.34
Web = 1.34 mm used for 105 mm OFL
(Equivalent to A P D S F S)
Single base

2° - Gunpropellant type LB 7 T - 1.2
Web = 1.2 mm - seven perforations
Used for 100 mm caliber, Navy Forces
Cool burning single base with 5 % Dinitrotoluene

3° - Candidate Lova gunpropellant
YH - 7 T
Web = 0.9 mm - seven perforations

The two first gunpropellants are fielded ; they are tested as references.

See hereafter on Table 3 and figure 2 for details on the two variants of YH-7T.

TABLE 3

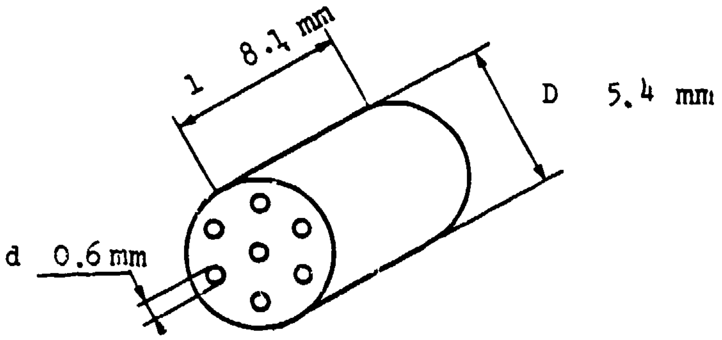
SOLVENTLESS GUNPROPELLANT LOVA CANDIDATES

DETAILS ON GUNPROPELLANT

	ENERGETIC FILLER	BINDER	COLOR	DIMENSIONS (mm)			DENSITY kg/m^3	
				Web	d	1/d	Real	filling of case
YH7T(0.9)1002	80% RDX (0-100 microns) graphite	20% HTPB Binder	black	0.90	0.60	1.5	1,530	520
YH7T(0.9)1003	78.6% RDX (0-100 microns) D.O.P	21.4 % HTPB Binder	white	0.92	0.61	1.5	1,520	540

FIGURE 2

SHAPE OF THE GRAIN



RESULTS : The results are presented hereafter in Tables 4 and 5.

TABLE 4

RESULTS ON LABORATORY TESTS

GUNPROPELLANT TEST	B 19 T (1.34)	LB 7 T (1.2)	CANDIDATE LOVA YH - 7 T
CRITICAL THICKNESS OF DETONATION	<8.5 mm	>60 mm	>15 mm
LENGTH BEFORE DETONATION	>1,200 mm	>1,200 mm	[illegible]1,200 mm *
GAP TEST	38 mm *	≤0.2 mm *	< 36 mm
REACTION TO SHAPED CHARGE	detonation *	no reaction	no reaction
30 KG FALLHAMMER (NO REACTION)	1,250 mm	≥4,000 mm	≥4,000 mm
CRITICAL HEIGHT (NO DETONATION)	>1,000 mm	>1,000 mm	>1,000 mm
HOT BALL TEST (FOR MASS 0.13 G)	450°C *	375°C *	625°C
FRICTION SENSITIVITY	112 N	0 % à 353 N	298 N
THERMAL INITIATION (5°C/mn)	166°C	170°C	234°C
IGNITION propane flame ignition time	230 ms	190 ms	5600 ms

* Estimated from similar gunpropellants

TABLE 5

RESULTS ON MODEL TESTS

GUNPROPELLANT TEST	B 19 T (1.34)	LB 7 T (1.2)	YH7T(0.9)
BULLET IMPACT	DEFLAGRATION	DEFLAGRATION	NO DEFLAGRATION
CRUSHING	DEFLAGRATION	DEFLAGRATION	NO REACTION
FIRE	DEFLAGRATION	DEFLAGRATION	NO DEFLAGRATION
SHAPED CHARGE	DETONATION *	DEFLAGRATION	DEFLAGRATION
SLOW COOK-OFF	DEFLAGRATION *	NO DEFLAGRATION	NO DEFLAGRATION

* Estimated from similar gunpropellants

III - POSSIBLE OBJECTIVES AND CRITERIA OF BEHAVIOR FOR GUNPROPELLANT

Three basic principles are to be respected :

Principle A : the performances of the gun propellant must remain at a proper level in the weapon.

Principle B : the cost of the total system must remain comparable : arguing on the cost of a separate component such as the gun propellant is of no significance for a property which is a total system property

Principle C : the improvement in vulnerability must be significant.

We will develop this third principle.

Three combined effects are undesired :

- the blast
- the projection
- the thermal flux

with their own **severity and probability**

If we have a gain on the blast, for example in reducing the detonability of the gun propellant, the progress will be of little interest if we maintain a high level of burning rate in a confined situation.

POSSIBLE PROGRESS IN THERMAL EFFECTS

Figure 3 gives for different gun propellants, in different packagings, the expected maximal radiant flux at 140 meters for 10,000 kg of product. The durations of fire are given in seconds. The maximal radiant flux are given in kilowatt by square meters. The assumptions for figure 3 are the following.

1. NEQ Constant = 10,0000 kg
2. Product = gun propellant
3. Constant out put = 50 kJ/m^2 at 140 meters
4. 1-3a/1-3b divide according to the french regulation
5. Ratio max. flux/average flux = 3
6. As comparison, liquefied propane, after a punching of the tank and fire of the exhausted gaz (product of class 2 - mass of propane of 10,000 kg)

The different points are coming from calculations, or experiments.

A French subdivision between products which burn with a considerable radiant heat (1-3 a products), and products which give an important radiant heat, but burn during a longer time or one item after the other (1-3 b) is visible on the figure 3.

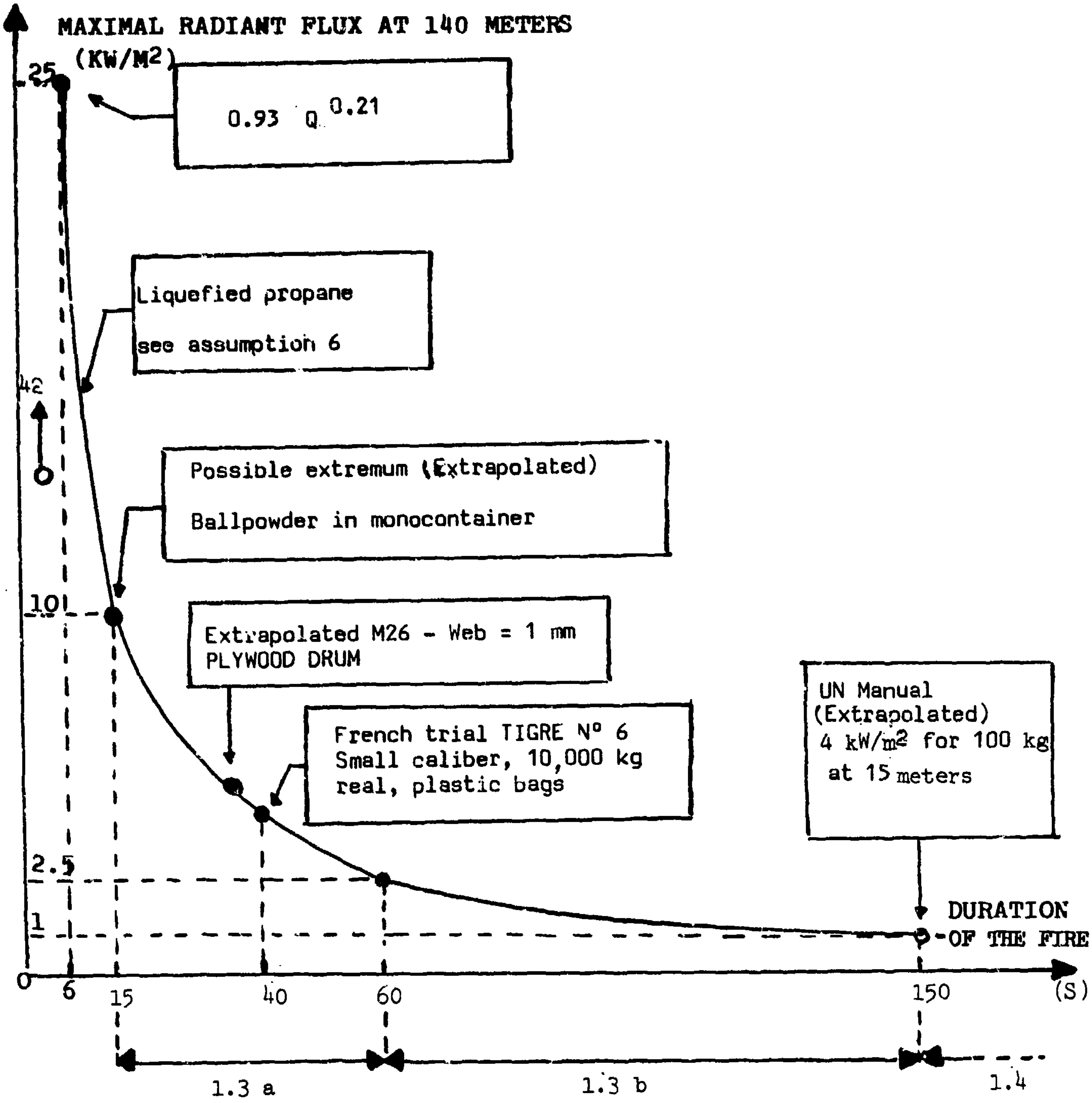


FIGURE 3

POSSIBLE BURNING BEHAVIORS FOR A 1.3. PRODUCT ; MAXIMAL RADIANT FLUX AT 140 METERS VERSUS DURATION OF THE FIRE

Figure 4 shows in function of :

- the distance to the center of the fire
- the level of the absorbed thermal flux at this distance,

the curves of available time to get a protected position before being burnt at the second degree.

The assumptions for figure 4 are the following :

1 Radial velocity of the evasive person = 5 m/s

2 Radiative source = constant flux

3 Duration of the fire = illimited

4 Burn = second degree

5 The thermal flux taken into account here is the thermal flux absorbed by the skin and not the incident thermal flux.

When the evasive action is not radial, figures at the right of the curves can be used.

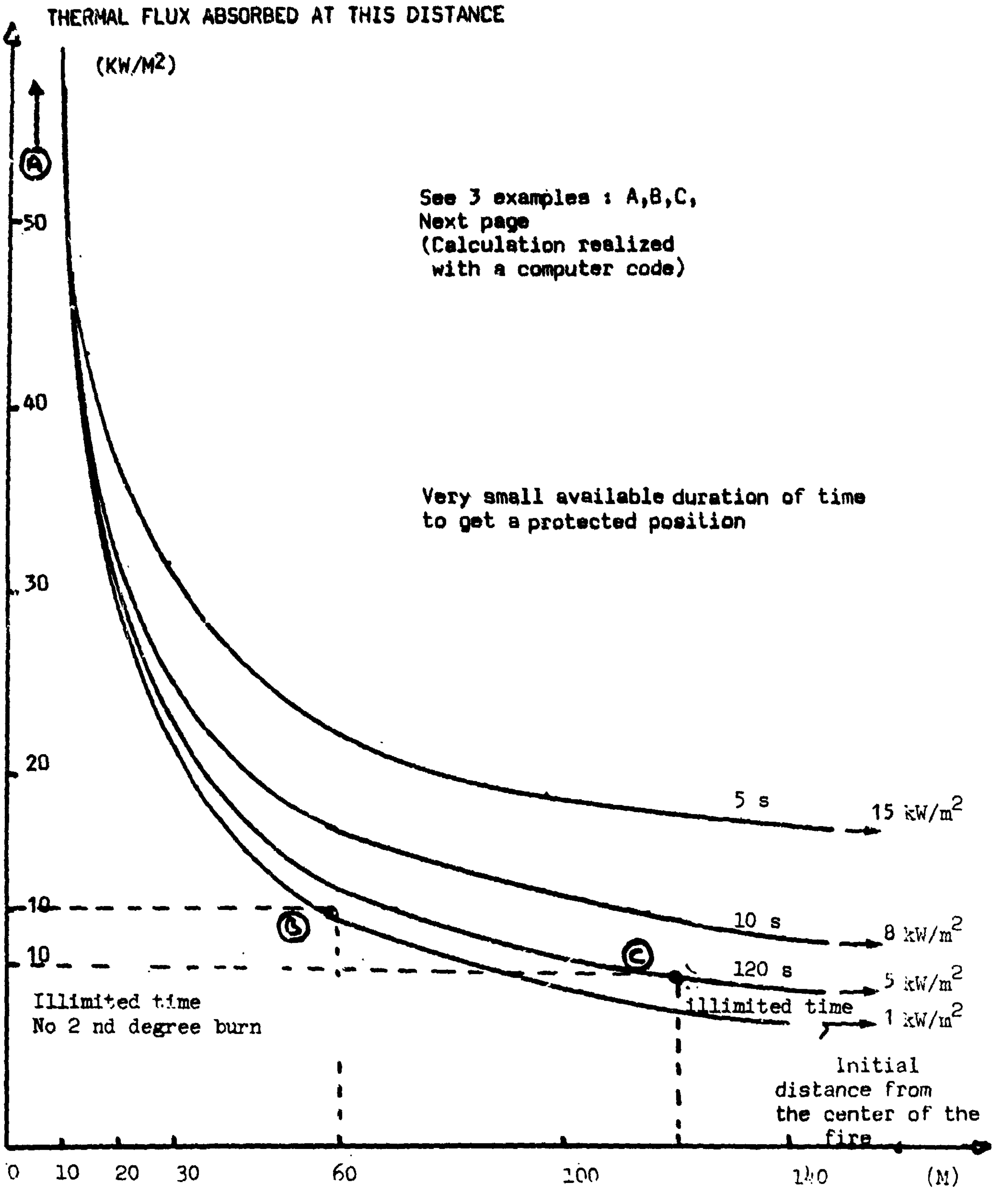


FIGURE 4

AVAILABLE DURATION OF TIME TO GET A PROTECTED POSITION BEFORE BEING BURNT AT THE SECOND DEGREE (bare skin - evasive velocity = 5 m/s)

EXAMPLE A

- A flame of a few square centimeters emitting a radiant flux of 70 kw/m^2 (not very hot flame). At 10 cm of it, the radiant flux is only of 0.05 kw/m^2.

Example : A hand passing in the flame of a gas-lighter is not burnt.

EXAMPLE B

- Assuming an absorbed flux of 12 kw/m^2 at 60 m from the center of a fire ball, a man running away with a velocity of 5 m/s can not be burnt to the 2 nd degree. (Case of 15,000 kg of gunpropellant in plastic bags)

EXAMPLE C

- Assuming an absorbed flux of 10 kw/m^2 at 120 m from the center of the fireball, a man running away with a velocity of 5 m/s has twenty seconds to get a protected position before being burnt at the 2 nd degree.

- END OF EXAMPLES -

From the curves of Figures 3 and 4, we can deduce it would be quite useful, to have in 1.3. Ammunitions, a divide value in order to have two types of ammunitions. The first type of ammunitions (1.3 a) would comprise ammunitions which burn with a considerable radiant heat. The second type (1.3 b) would comprise ammunitions, the thermal effects of which would be limited. A fire of such 1.3 b products would allow near people to escape from their place safely, in a majority of situations.

CONCLUSIONS

Significant efforts have been reported in developing new less sensitive gun propellants. These efforts must be translated in significant improvement in vulnerability of weapons. Defining clearly the objectivos, would be an essential step. Thermal effects can be very lethal in some situations. It could be useful to define 1-3 b munitions which would burn with a not too high radiant heat.

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EFFECTS OF EXPLOSION ON ADJACENT BAY BLOWOUT WALLS

by

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Explosives processing plants are often configured as adjacent bays, the sixth wall of each being a frangible blowout wall. As illustrated in Fig. 1, if an explosion occurs, one wishes to know whether the blowout wall will be pushed in or pulled out by the blast wave. If pushed in, the explosives operation in that bay may be at risk from blowout wall debris. The plant investigated in this study has processing bays that are nominally 24-ft deep, 20-ft wide, and 12-ft high. Charge weights considered were 25 and 100 lbs of PBX 9404.

Figure 2a shows a schematic representation of a single processing bay and an attached wall representing the blowout wall of an adjacent bay, upon which pressure measurement stations are designated. This configuration was subsequently used in a series of scale model experiments. Figure 2b shows an axisymmetric approximation of the processing bay and attached wall. The diameter of the axisymmetric model was chosen to preserve the cross sectional area of the rectangular bay.

A finite difference, axisymmetric numerical model of the processing bay was studied using the SALE[1] computer code. Computational cells were approximately

15 in. x 14 in. At time zero, explosive modelled with suitable density and internal energy at the center cell of the bay was allowed to release its energy instantaneously. Pressure and specific impulse at three points on the simulated adjacent blowout wall were calculated and are shown in Fig. 3 for the middle location. These showed an initial inward pressure load of sufficient impulse to cause concern that the blowout wall would fail catastrophically.

These disturbing analytical results led to scale model confirmatory experiments. Figure 4 shows a one-eighth scale steel model of the processing bay to which a rigid steel wall has been appended to model the blowout wall of an adjacent bay. Three pressure transducers were installed in this wall at positions shown in prototype scale in Fig. 2a. Explosive charges were cylinders of PBX 9404 weighing 22- and 88-g. Figure 5 shows a charge being suspended on monofilament line at the center of the model. Charges were detonated from the bottom.

The transducers selected for this application were the new piezoresistive, silicon diaphragm, full active arm bridge, series 8510 marketed by Endevco. The major problem associated with pressure measurements in a metal wall subjected to mechanical shock is acceleration induced signal in the transducer. The specified sensitivity of this transducer to acceleration along its sensitive axis is typically 0.3 psi/1000 g's. The DC response of the pressure transducers enabled us to make simple static end-to-end calibrations with a dead weight tester. Photosensitivity of the transducers was successfully sidestepped by carefully removing the protective screen over the diaphragm and completely coating the diaphragm with a light layer of opaque grease. The grease was standard silicon vacuum grease loaded with approximately 30% by weight of dry copier toner. Damping created by the grease applied to the diaphragm would affect the frequency response somewhat but, if the coating is just sufficient to cover the diaphragm, the effect is negligible.

The cabling in the system consisted of a 30-in.-long transducer pigtail (4 cond, #32AWG, shielded) connected to 115-ft length of 15 pair cable (#22 AWG, twisted, shielded pair), which in turn connected to a 30-ft length of 2 pair (#22 AWG, twisted, shielded pair) that terminated via a single connector to the signal conditioner. The low side of the excitation was connected to the shield in the pigtail and was grounded at the test fixture. The shields of the pairs were connected through and maintained separately until the connection at the pigtail where they were tied together and grounded. The signal pair shield was tied to the signal conditioner guard, and the excitation pair shield was insulated and floating at the signal conditioner.

The signal conditioners were Ectron 776B units. These consist of a high gain differential amplifier, an excitation supply, and an adjustable calibration supply contained in a shielded box maintained at guard voltage. The power transformer primaries, the final amplification stages, and some control circuitry are outside of the guard shield but inside the main cabinet maintained at local system ground. Each signal conditioner is self contained and, with the exception of the primary power feeds and the local ground, are completely isolated. This configuration, along with proper cabling, provides freedom from ground loop induced noise and noise from common mode signals. A calibration signal that matches the full-scale output of the transducer is applied to the input of the amplifier just before zero time. The known signal level is recorded through the same path as the transducer signal, enabling one to use it as a calibration reference for the unknown signal.

The bandwidth of the signal conditioners is 100 kHz. The excitation voltage to the transducers was set to 10.00 VDC at the signal conditioner.

The output of each signal conditioner was attenuated to match the input level (± 1.414 V) of a Honeywell 101 Instrumentation Tape Recorder. The input to the recorder was a wide-band Group I IRIG FM channel. Recording speed was 120-in./s, providing an effective bandwidth of DC to 80 kHz. The very stable tape speed of this unit was relied on to eliminate time base errors and FM frequency shifts.

The data reduction portion of the system used the reproduce portion of the tape recorder to regenerate the analog signal, a Nicolet 660B signal analyzer to time domain digitize the analog signal, and an HP 85 computer and peripherals to store and plot the data.

The overall system is shown in Fig. 6.

Figures 7 and 8 show measured pressure raw data for 22- and 88-g shots. Pressure scales directly, but time and impulse must be multiplied by the geometric scale factor of eight to transform these data from model to prototype scale. Each pressure record is characterized by multiple short duration peaks, sources of which are the various reflecting surfaces in the processing bay, followed by a long negative phase of small magnitude relative to the positive phase. In Table I, peak pressures and positive specific impulses calculated using the axisymmetric computer model are compared with measurements from the scale model experiments. Except at the far position for the smaller charge, the measured data confirm to within an order of magnitude the calculated pressures and impulses.

Having confirmed the substantial inward load, the blowout wall was analyzed for structural failure. The building was constructed in the 1950's, and the only information on the structure of the blowout wall was a drawing note:

> "Panels: - Robertson, 'Q-Panel' Type 'A' 14 B&S Ga. 3SH14
> Aluminum with 1-1/2-in.-thick 'Fiberglas' Insulation Type
> PFG or Equal."

TABLE I

CALCULATED AND MEASURED LOADS ON ADJACENT BLOWOUT WALL

CALCULATED AND MEASURED LOADS

CHARGE WEIGHT	MEASUREMENT LOCATION	PEAK PRESSURE (psi)		POSITIVE IMPULSE (psi-ms)	
		CALCULATED	MEASURED	CALCULATED	MEASURED
100 LBS	NEAR	25	20	32	44
	MIDDLE	16	14	53	47
	FAR	7	16	28	56
25 LBS	NEAR	8	10	14	24
	MIDDLE	5	5	28	24
	FAR	[illegible]	5	1.5	28

Perusal of Laboratory archives, inquiry to the H. H. Robertson Co., and search of an old building materials landfill resulted in neither detailed drawings nor a sample of the blowout wall panels used in this building. Figure 9 shows the panel cross section as determined from on-site measurements. Ideally a sample of this complex cross section would be available for experimental determination of its moment capacity. Absent this option, structural properties were calculated[2] and are summarized in Fig. 9. Ultimate moment carrying capacity was assumed to occur when the webs of the corrugated front panel buckled.

In all cases, the positive phase duration of the load is less than 25% of the equivalent single degree of freedom natural period of the blowout wall panel.

Peak deflections were calculated using linearized forms of the measured pressure traces and Newmark numerical integration. These results were checked by converting the positive phase pressures to simple, zero-rise-time triangular pulses that preserved peak pressures and specific impulses of the measured data. Peak deflections were then obtained using the standard procedure found in TM5-1300.[3] Peak deflections are summarized in Table II and confirm that inward catastrophic failure of the blowout wall is likely.

Qualitative numerical experiments were run using the axisymmetric finite difference model to see if extension of the partition between processing bays would limit the pressure loads on adjacent blowout walls. Extensions of up to 10 ft were tried, and although pressures were reduced, sufficient reduction did not occur. These calculations are summarized in Fig. 10. No scale model tests were run in this configuration. Figure 11 shows the simple interior blowout wall bracing system eventually used in this building to limit inward deflection of the blowout walls. The blowout walls are not attached to the braces.

For a particular processing bay configuration, ~~we have~~ it has been shown that adjacent bay blowout walls are at risk for catastrophic inward failure. An axisymmetric computer model of the fluid flow associated with an explosion proved useful in this configuration for determination of loads on adjacent blowout walls. Existing blowout walls found to be vulnerable can be easily braced. Designers of blowout walls for new explosives processing facilities must consider the possibility of inward failure.

TABLE II

CALCULATED BLOWOUT WALL DEFLECTIONS

CALCULATED DEFLECTIONS DUE TO MEASURED LOADS			
CHARGE WEIGHT	MEASUREMENT LOCATION	PEAK PANEL DEFLECTION (IN)	PEAK DEFLECTION / YIELD DEFLECTION
100 LBS	NEAR	117	66
	MIDDLE	36	20
	FAR	50	28
25 LBS	NEAR	10	6
	MIDDLE	10	6
	FAR	12	7

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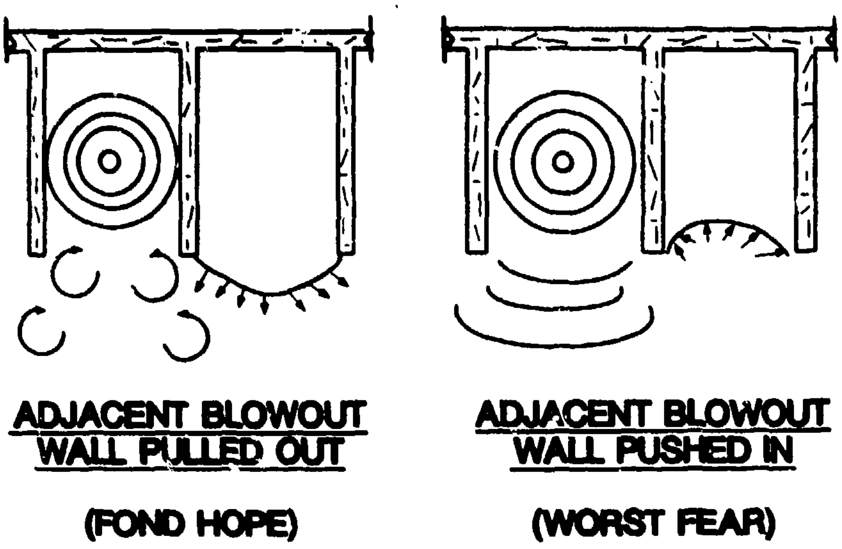
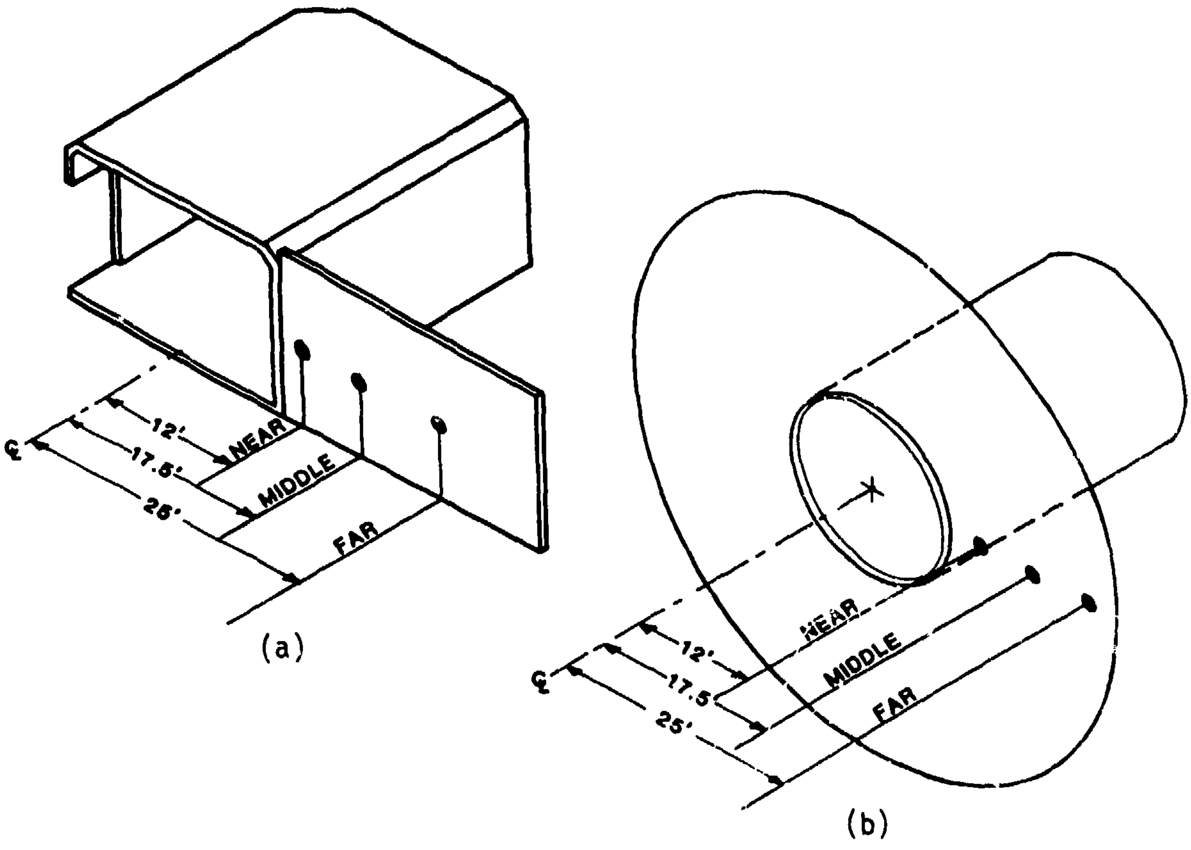

ADJACENT BLOWOUT WALL PULLED OUT
(FOND HOPE)
ADJACENT BLOWOUT WALL PUSHED IN
(WORST FEAR)

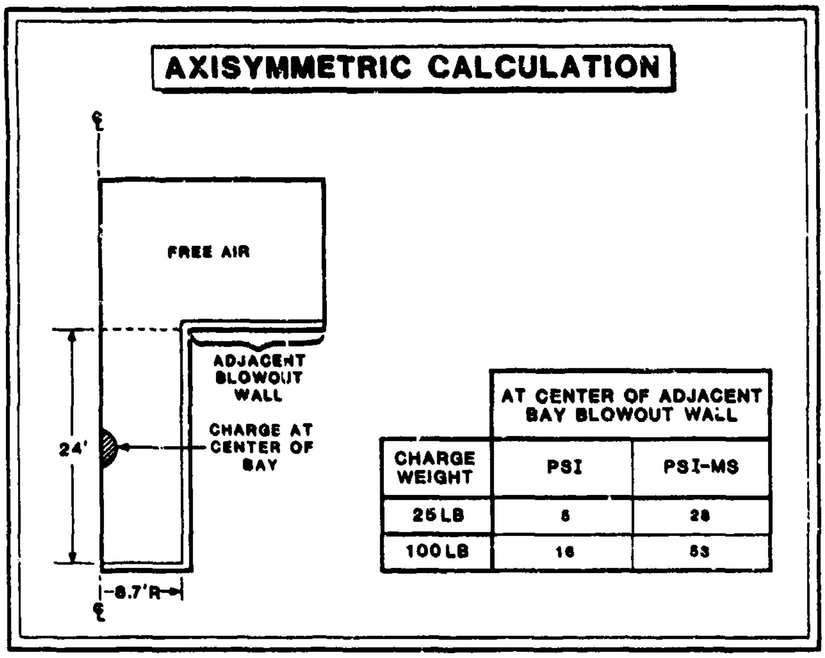
Fig. 1. Adjacent explosives processing bays.



(a)

(b)

Figs. 2a and b. Explosives processing bay and axisymmetric model.



	AT CENTER OF ADJACENT BAY BLOWOUT WALL	
CHARGE WEIGHT	PSI	PSI-MS
25 LB	5	28
100 LB	16	53

Fig. 3. Calculated pressure and specific impulse.

Fig. 4. One-eighth scale model explosives processing bay.

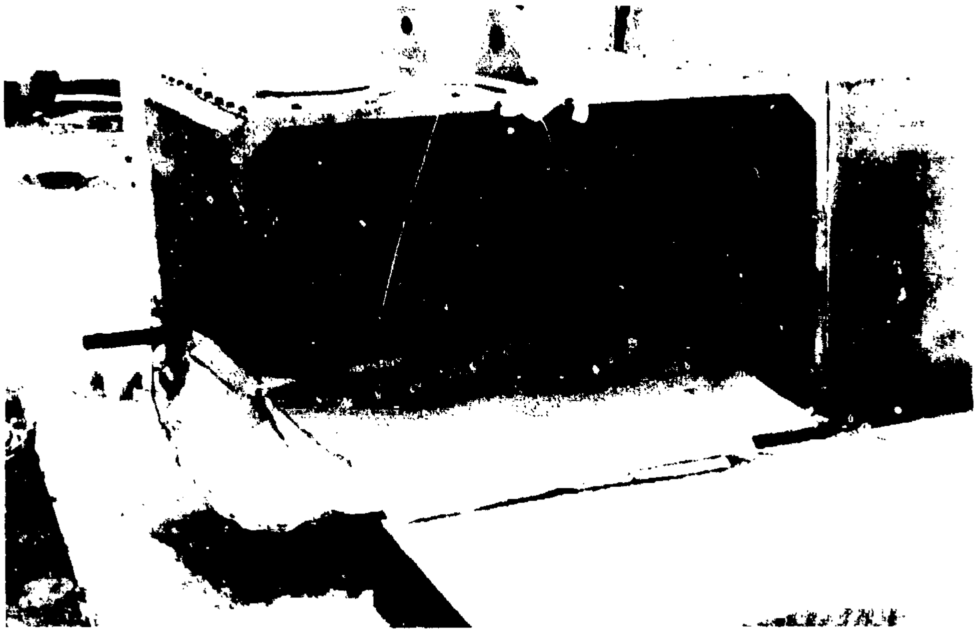


Fig. 5. Explosive charge in scale model processing bay.

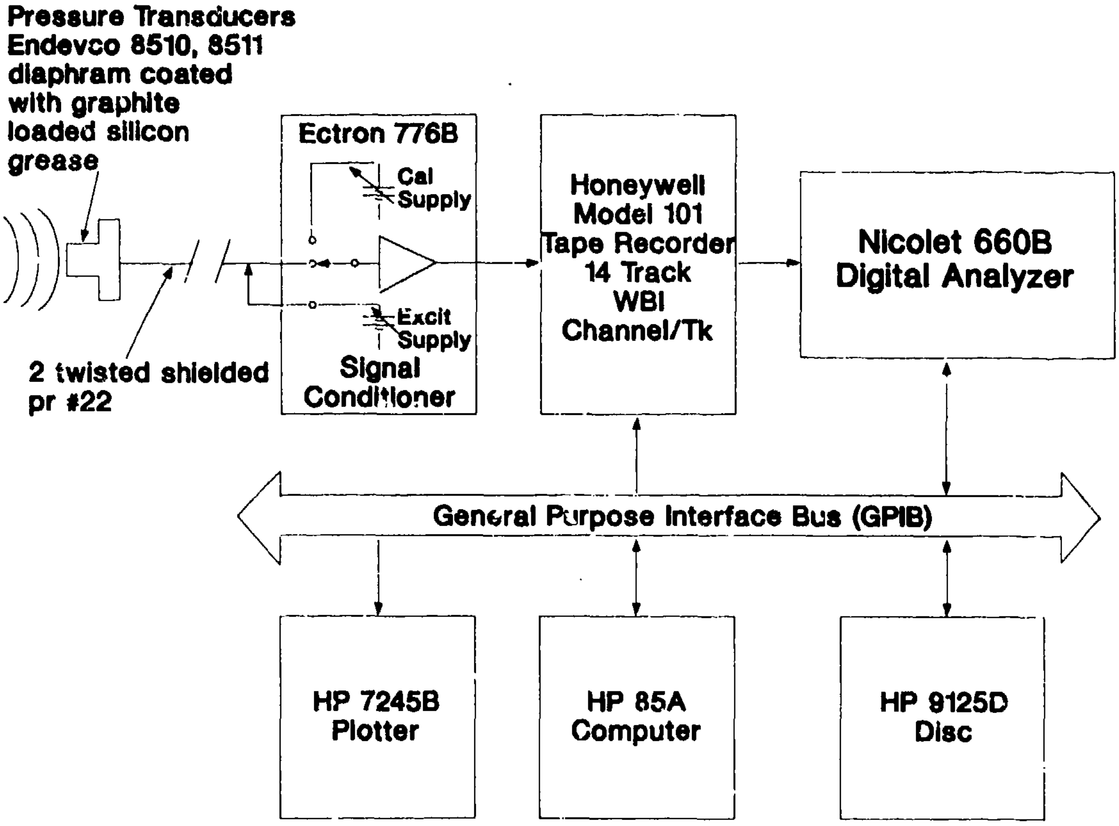
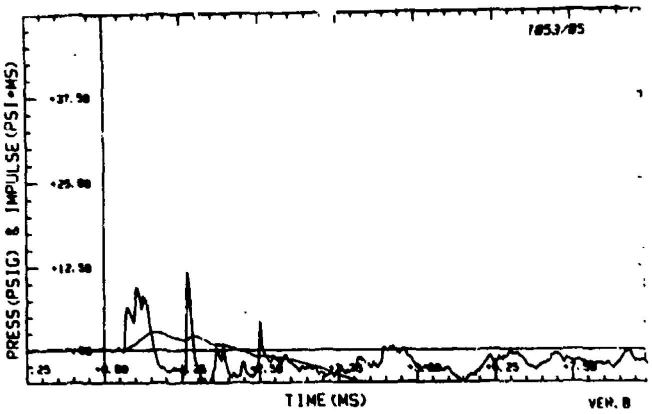
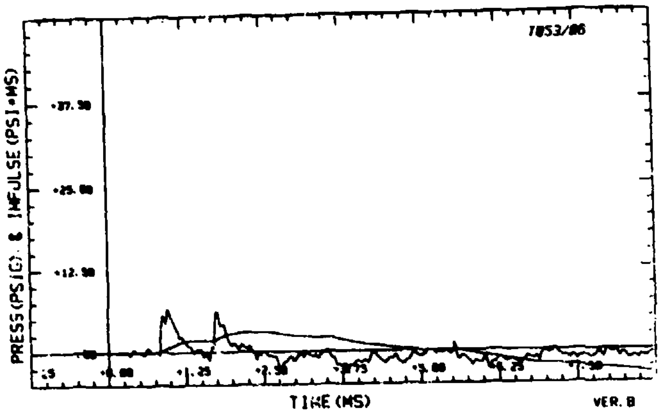


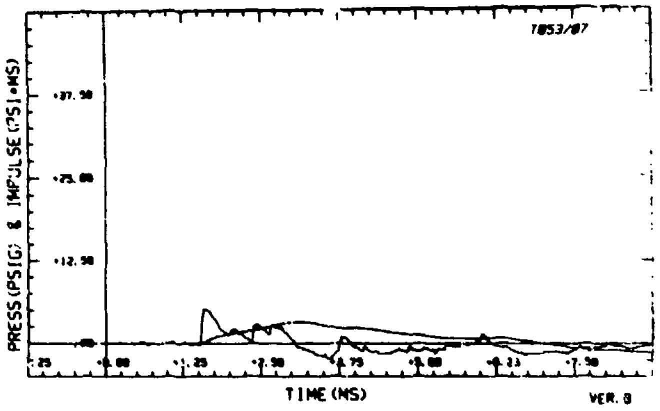
Fig. 6. Data acquisition system.



WALL NEAR

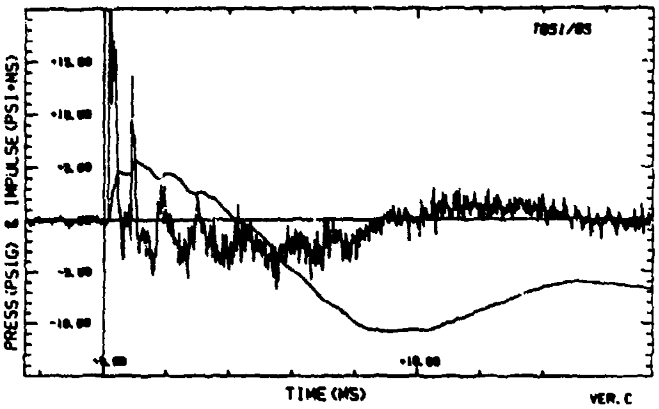


WALL MIDDLE



WALL FAR

Fig. 7. Measured pressure and impulse, 22-g charge.



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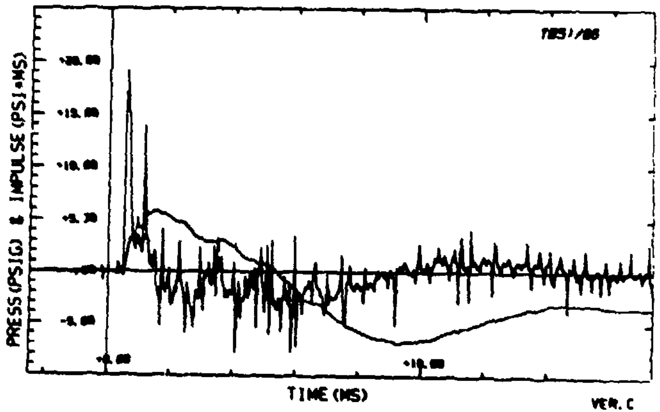
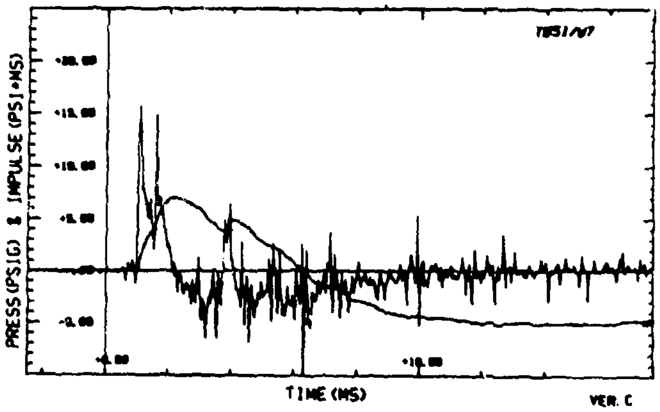
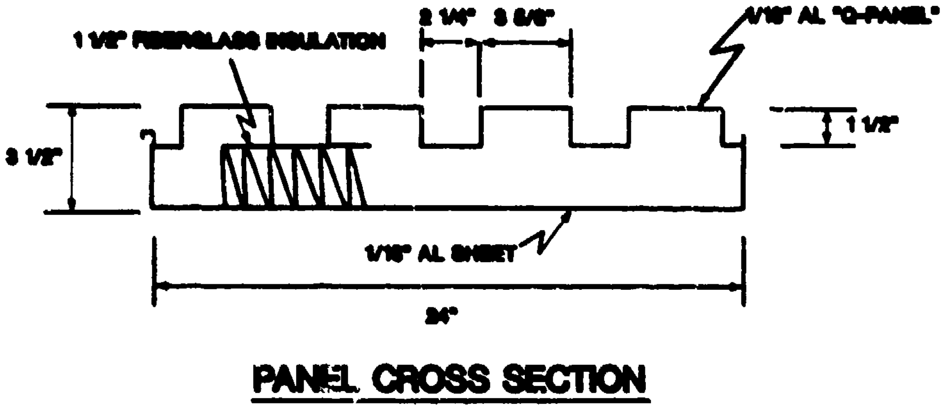


WALL MIDDLE



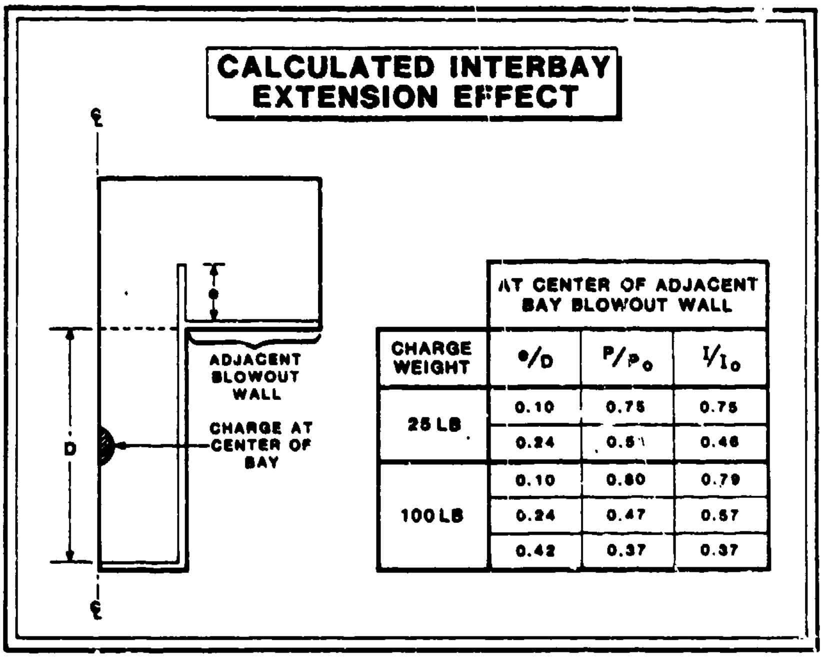
WALL FAR

Fig. 8. Measured pressure and impulse, 88-g charge.



CALCULATED PANEL PROPERTIES	
WEIGHT OF COMPOSITE PANEL	2.30 LB/FT²
DEFLECTION AT WEB CRIPPLING	1.78 IN
LOAD AT WEB CRIPPLING	1.08 PSI

Fig. 9. Structural properties of blowout wall.



	AT CENTER OF ADJACENT BAY BLOWOUT WALL		
CHARGE WEIGHT	e/D	P/P$_o$	I/I$_o$
25 LB	0.10	0.75	0.75
	0.24	0.51	0.46
100 LB	0.10	0.80	0.79
	0.24	0.47	0.57
	0.42	0.37	0.37

Fig. 10. Calculated effect of extending interbay partition.

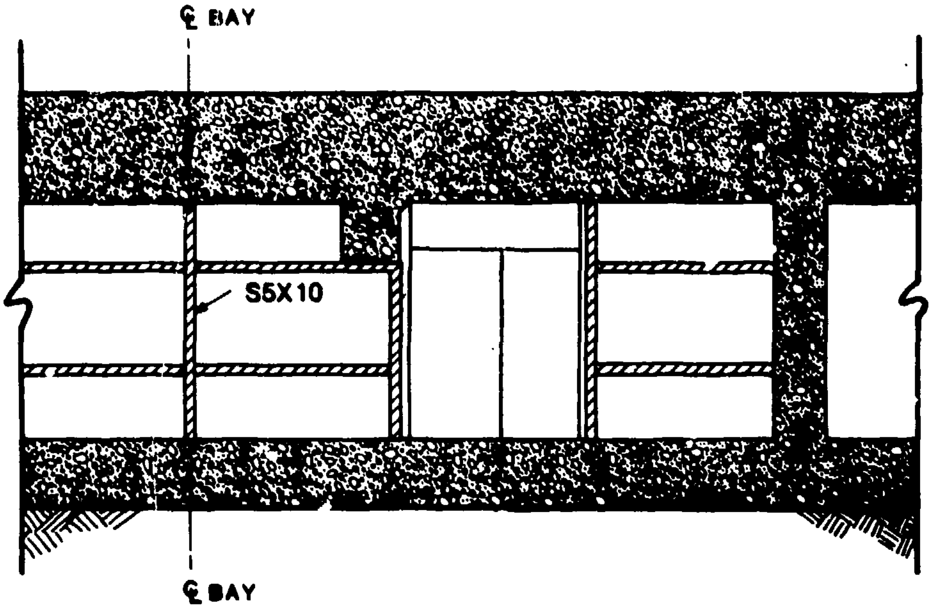


Fig. 11. Internal bracing system for blowout walls.

BLAST VENTING FROM A CUBICLE

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ABSTRACT

This work presents a computational study of blast venting from a cubicle, for a charge detonated at the center of the cubicle. The study is carried out using the PISCES 2DELK code employing modern, second order accurate, flow calculations. The computational model has provisions for varying the charge weight, the venting area, and the frangible panel mass. The results of the calculations are presented in the form of wall impulse and average pressure time-histories. Comparison with previous work is included.

INTRODUCTION

The design of vented chambers, with or without a frangible panel, requires a means for estimating the impulse loading on the walls. Previous work includes experimental data in the form of wall pressure time-histories [1], simplified mathematical models for the effects of a frangible panel [2], and some numerical flow calculations of shock reflection and reverberation inside the structure [3]. A recent study [4] combined theoretical results and experimental data and reduced them to a single "working curve" using similarity methods.

The purpose of present work is to study, in detail, few cases of blast venting, and to compare them with reported results. We employ a numerical solution of the full flow problem, including both the initial intense shock reflections and the later gradual venting. Frangible panels are treated as undeformable bodies with finite mass, and are allowed to move through the flow field by the action of the surrounding pressure.

The numerical solution is obtained with the PISCES 2DELK code, using its second order Euler processor [5]. The results of the calculations are presented in the form of pressure contours and velocity vector fields at selected times, and time-histories of pressure and impulse on the walls.

STATEMENT OF THE PROBLEM

To conform to the axial symmetry of the numerical code, we consider a cylindrical cubicle, having equal length and diameter. (Fig. 1). One end of the cylinder is assumed to be completely closed, whereas the other end has a circular opening to represent the venting area. The venting area may be left open, or it may be covered by a frangible panel. An explosive charge is assumed to be detonated at the center of the cylinder.

The parameters in the problem are:

V - the volume of the cubicle,
W - the energy of the explosive charge,
A - the venting area,
M - the areal density of the frangible panel.

These parameters define the problem comletely, when the equation of stste of air and the initial state (pressure and density) are given. The solution of the resulting flow field should provide the impulse I imparted to the walls, which is the central objective of the calculation.

The specific dimensions of the cubicle were chosen such that its volume is one cubic meter. A nominal explosive energy of 4.5 MJ was taken, representing one Kg. of TNT. Three cases of open vents were calculated, and one case of a frangible panel. These few cases are not intended to provide design data. Rather, they are regarded as a feasibility study to assess the methodology of using detailed flow calculations, to validate or calibrate existing simplified models.

The parameters of the runs are as follows:

$V = 1\ m^3$,
$W = 4.5$ MJoule,
$A = 0.916$, 0.554 and 0.180 m^2, for $M=0$,
$A = 0.554\ m^2$ for $M=10\ Kg/m^2$.

THE COMPUTATIONAL MODEL

The computational model consists of a grid of 1.44m×0.72m with computational zones of 0.03m×0.03m. The cubicle, with dimensions of 1.08m(length)×0.54m(radius), is imbedded in the computational grid as shown in Fig. 2. The cubicle walls are represented in the model by defining the zones along the walls as cells with rigid boundaries. Along the sides of the computational grid we employ boundary conditions. The axis of symmetry and the closed end of the cubicle are given a rigid wall condition , allowing motion parallel to the wall only. The rest of the boundaries are assigned a "continuative flow" condition, which prevents reflections from the boundaries, thus simulating an infinite medium. The continuative flow condition is an approximation that saves computational resources while sacrificing some accuracy in the results.

The explosive charge is simulated by a sphere of dense hot air, having the same energy and mass, but extending over a larger volume. (A sphere of 0.2122m radius, four times larger than the actual radius of the 1 Kg. TNT charge). Again, this approach is employed to save computer resources, since the actual charge would have required much finer zoning, and consequently much smaller time steps. It is expected that the long term impulse on the walls will not be affected appreciably by this approximation, as was actually verified in a test case. (Reported in the next section).

The calculations reported here consumed a total of 180 hours on a VAX 750 machine.

RESULTS

As an example, results for the case $A=0.554m^2$, $M=10Kg/m^2$ are shown (Figs. 3-6). Fig. 3a is a velocity vector plot at time=mS. The effects of shock reflection from the walls are clearly seen. A later time is shown in Fig. 3b, where the frangible panel moved sufficiently to clear the opening wall, so that venting started on the perimeter. At a later time, venting is established, and the gas flows around the panel(Fig. 3c). At this time, the panel was removed from the computational grid (representing breakage). This did not cause an appreciable change in the venting process, since the actual venting area at the perimeter of the panel was roughly the same as the opening area. At much later time the flow pattern changes to that of an uncovered opening: a stream along the axis of symmetry (of the kind represented by Fig. 3d, for $\bar{A}=.18$, $M=0$).

The main result of the calculation is the wall impulse. It is obtained by integration of the pressure on an assigned section of the boundaries. The process involved both spatial and temporal integration, and is carried out automatically by the code. Two walls were designated in these calculation: the "back", or the closed end of the cubicle, and the "side", or the cylindrical wall of the enclosure. Time-histories of the impulses on these walls are given in Figs. 4.

Wall pressure at selected points could also be shown, but we chose to display averaged wall pressures. Point pressures are sensitive to local reflection effects, whereas the averaged pressures represent the global loading on the wall. The averaged pressure was obtained by appropriate time differentiation of the impulse curves. (Figs. 5).

The inclusion of a frangible wall is demonstrated in Fig. 6, where two cases with an opening of $\bar{A}$=.554, with and without a frangible wall, are compared. The areal mass density is 10Kg/m^2, which represents a panel having 4% of the mass of a typical hardened wall in a 60m^3 chamber.

To evaluate the effect of the initial conditions, we compared the resulting impulse for two cases having the same vent area, but different initial volume of the charge. In the standard case the charge is modeled by a sphere of 25Kg./m^3 density, and in the test case the density is 200 Kg./m^3. As would be expected, the average pressure has sharper peaks in the "dense" charge case, but their contribution to the total impulse is practically identical to the standard case, the differance being less than 5% (Fig. 7).

DISCUSSION

A summary of the results is given in Table 1, for the impulse, and in Table 2, for the pulse duration. I_B and I_S are the impulses of the back wall and the side wall, respectively. $\bar{I}_{av}$ is the reduced impulse, averaged, somewhat arbitrarily, over the two walls. The reduced impulse is defined by $\bar{I}=Ia_oA/poV$, a_o being the speed of sound in the ambient air. Table 2, shows the pulse duration T, and the reduced duration $\bar{T}=a_oTA/V$. The reduced parameters are presented to enable a simple comparison with previous work.

According to the similitude analysis, the reduced impulse of the quasi-static pressure is a constant for a given charge per unit volume. The three values in table 1 are almost a constant (7.86±0.12). This is unexpected, since the impulses in Table 1 are total impulses (shock reflection+quasi-static pressure). The present results which include the shock pressure contribution, are indeed higher than values presented by previous workers for the quasi-static pressure only. The present average value of 7.86 is 20% above the value given by Kulesz and Friesenhann ([2], Fig. 4) and 70% above the best fit to the data compiled by Anderson et al. ([4], using $W/P_0V=450$ or $\bar{p}=17.2$). It is interesting to note the behaviour of the quasi-static impulse values calculated for our configurations by Tancreto's equation 3a (ref. 1c). These values are 2, 4 and 13.2 MPa-mS for $\bar{A}=.916$, .554 and .18 respectively. Compared with our total impulse values of 2.8, 4.4 and 13.6 MPa-mS, one can see that as the vent area gets smaller, the quasi-static impulse values tend to become very nearly the same as our total impulse values. However, the present calculations disagree with the TM5-1300 manual [6], which predicts a shock reflection impulse of 4.2 MPa-mS, 50% higher than the impulse for $A=0.916m^2$.

The case with frangible panel yielded an impulse 42% higher than the corresponding uncovered case. The code of Kulesz and Friesenhann predicts an increase of only 4% for this case.

The pulse durations (Table 2) range from 4.4 mS to over 50 mS, depending on vent area and the presence of a frangible panel. The reduced duration varies between 1.35 and 3.00, in the same range. This result does not agree with the simplified models, which predict a constant reduced duration for a given charge per unit volume, for a pure quasi-static pressure venting process. However, this result seems to be consistent with the compiled experimental data [Anderson at al], which appears to have much larger scatter than the reduced impulse. A more extensive study is required to clarify this point. The parameter $\bar{T}\,(\bar{A})^{1/2}$, shown in the last column of Table 2, is almost a constant, for the cases considered. There is no simple explanation of this result, at present.

Table 1.

Impulse for explosion venting
V=1 cu. meter, W=4.5 MJ (1 Kg. TNT)

Vent Area A, m^2	Panel Mass M, $Kg./m^2$	Impulse(back) I_B, MPa-mS	Impulse(side) I_S, MPa-mS	Reduced Imp. $\bar{I}_{av}$ (averaged)
0.916	0.	2.8	2.25	7.73
0.554	0.	4.46	4.04	7.88
0.180	0.	13.6	12.9	7.98
0.554	10.	6.3	5.8	11.2

Table 2.

Pulse duration for explosion venting
V=1 cu. meter, W=4.5 MJ (1 Kg. TNT)

Vent Area A, m^2	Panel Mass M, $Kg./m^2$	Duration T, mS	Reduced duration $\bar{T}$	$\bar{T} * \bar{A}^{1/2}$
0.916	0.	4.4	1.35	1.29
0.554	0.	8.3	1.53	1.14
0.180	0.	50+	3.00	1.27
0.554	10.	9.3	1.72	

CONCLUSIONS

A computational model, to be used with the PISCES 2DELK code, was presented. The model allows a complete analysis of the venting problem, covering both the shock reflection phase and the quasi-static pressure release phase, and including frangible panel effects. Few cases were presented. Comparison with previous works cited indicates that further work is needed to resolve points of disagreement and turn our model into a routine working tool.

Acknowledgments

The authors wish to thank the management and the staff of Dep. 45 for their hospitality, and for the generous support in computer services.

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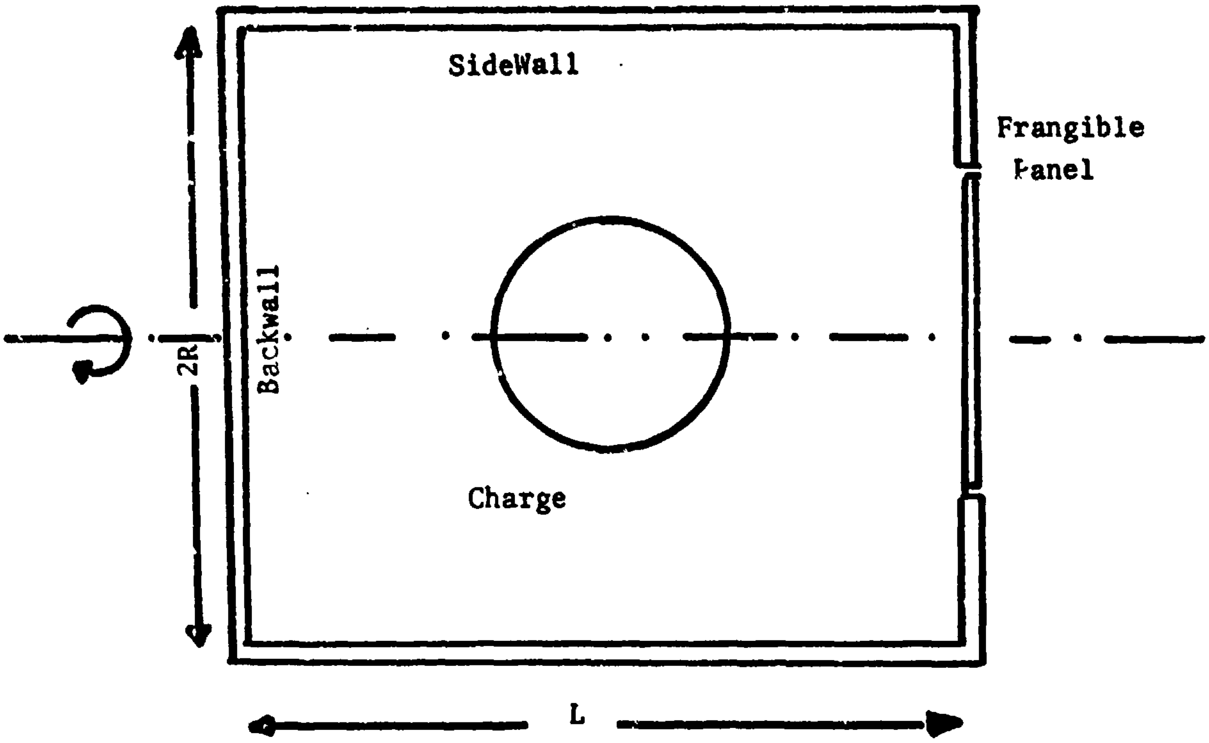

Fig 1: Schematic of Vented Cubicle
2R=L=1.08m (Volume=1m^3)

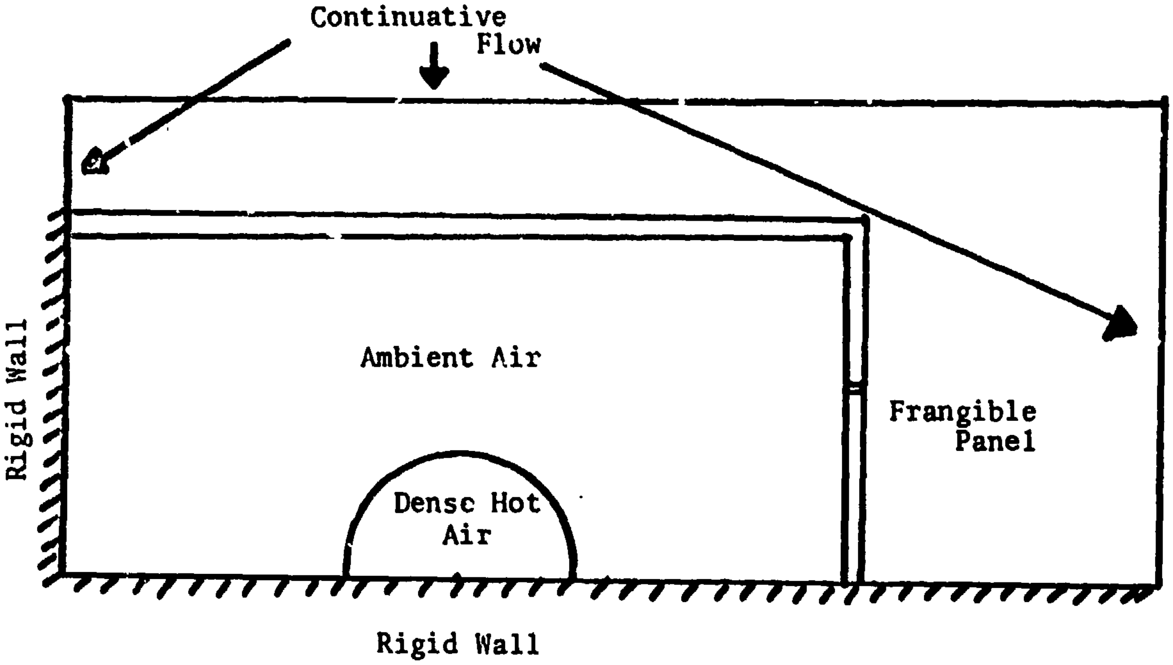

Fig.2: The Computational Grid
0.72m×1.44m (24×48 cells)

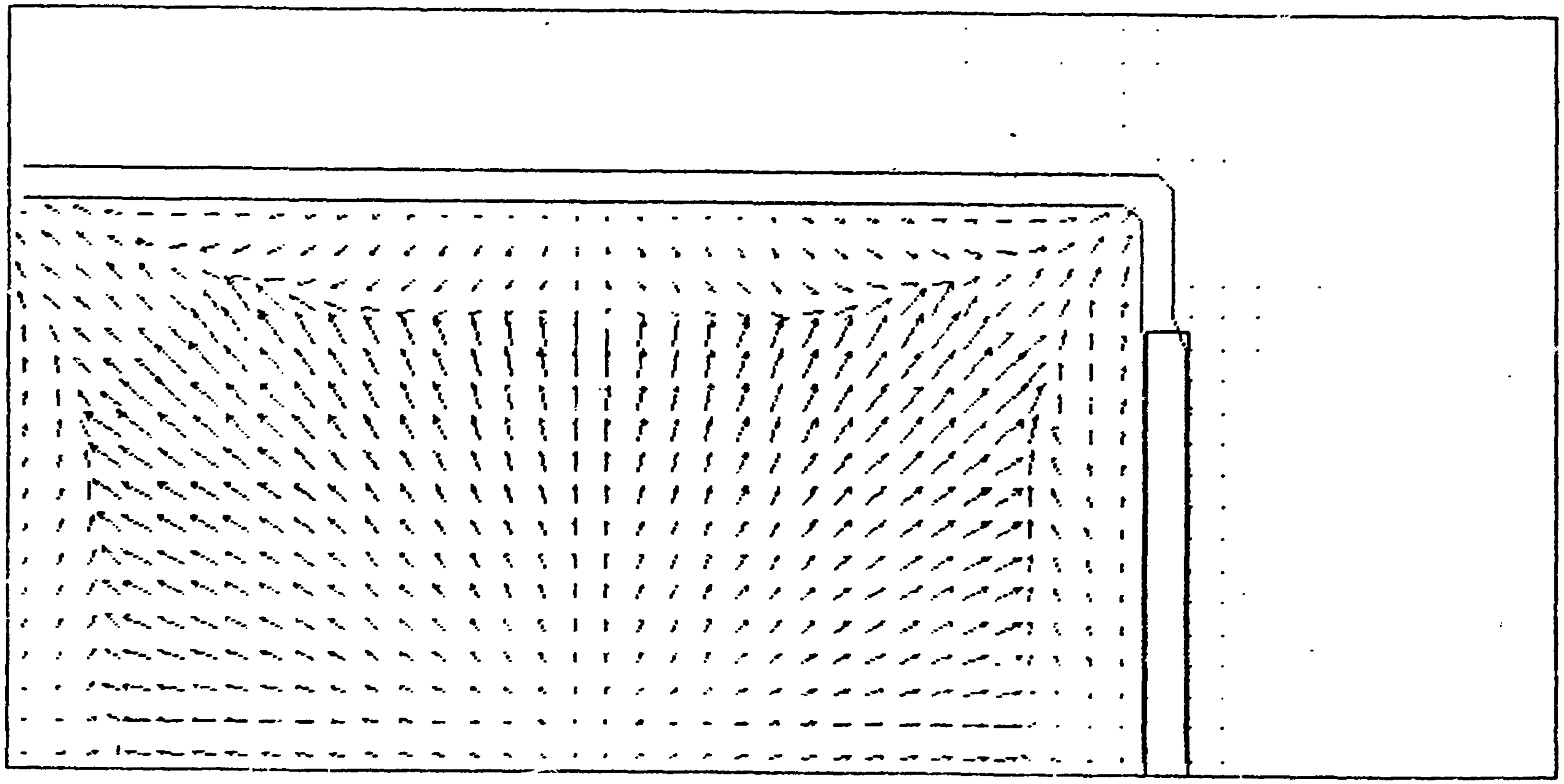

Fig 3a: Velocity Vector Plot at t=0.3mSec

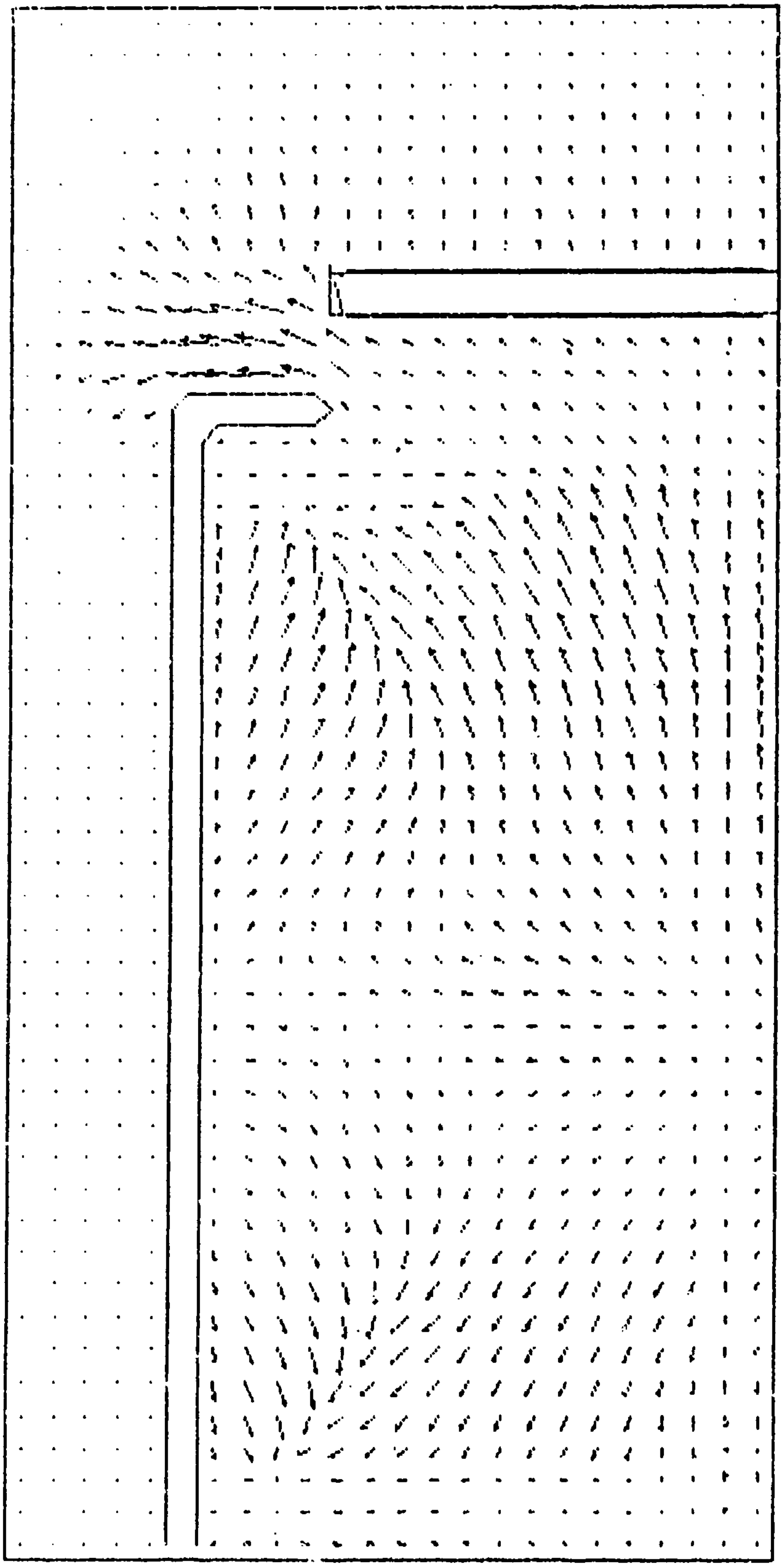

Fig 3b: Velocity Vector Plot at t=1.1mSec

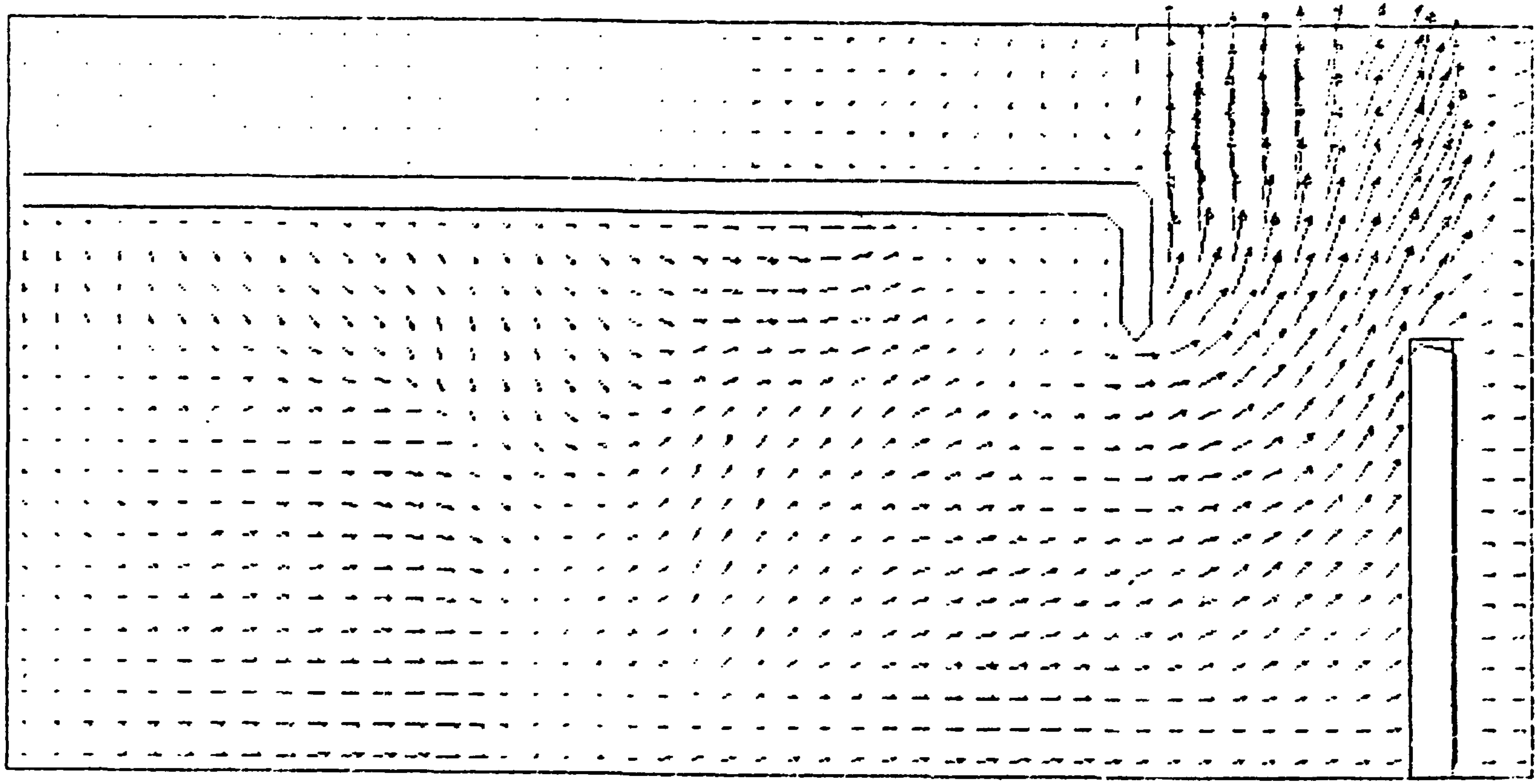

Fig 3c: Velocity Vector Plot at t=1.9mSec

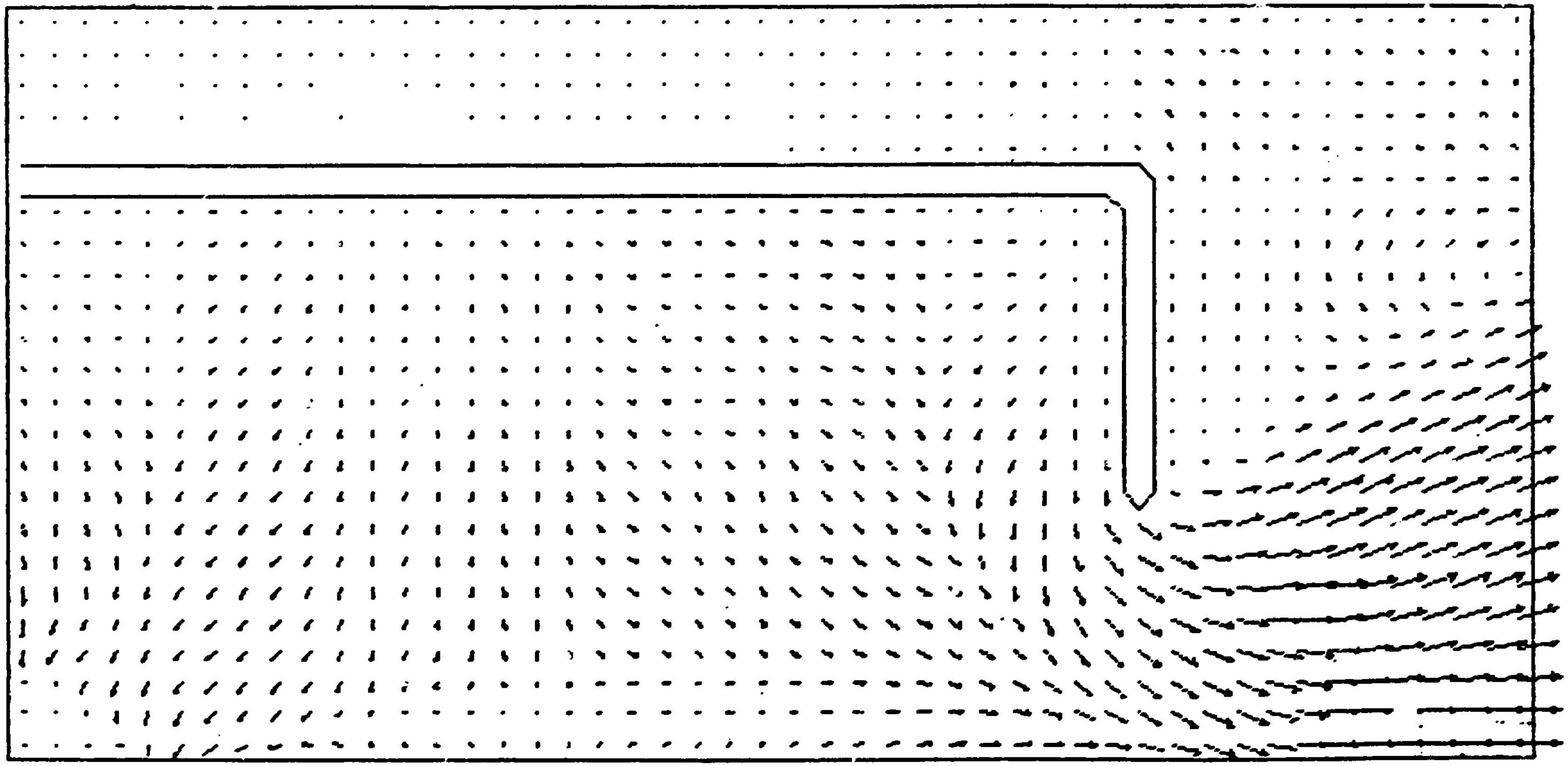

Fig 3d: Velocity Vector Plot at t=1.34 mSec (A=.18, M=0)

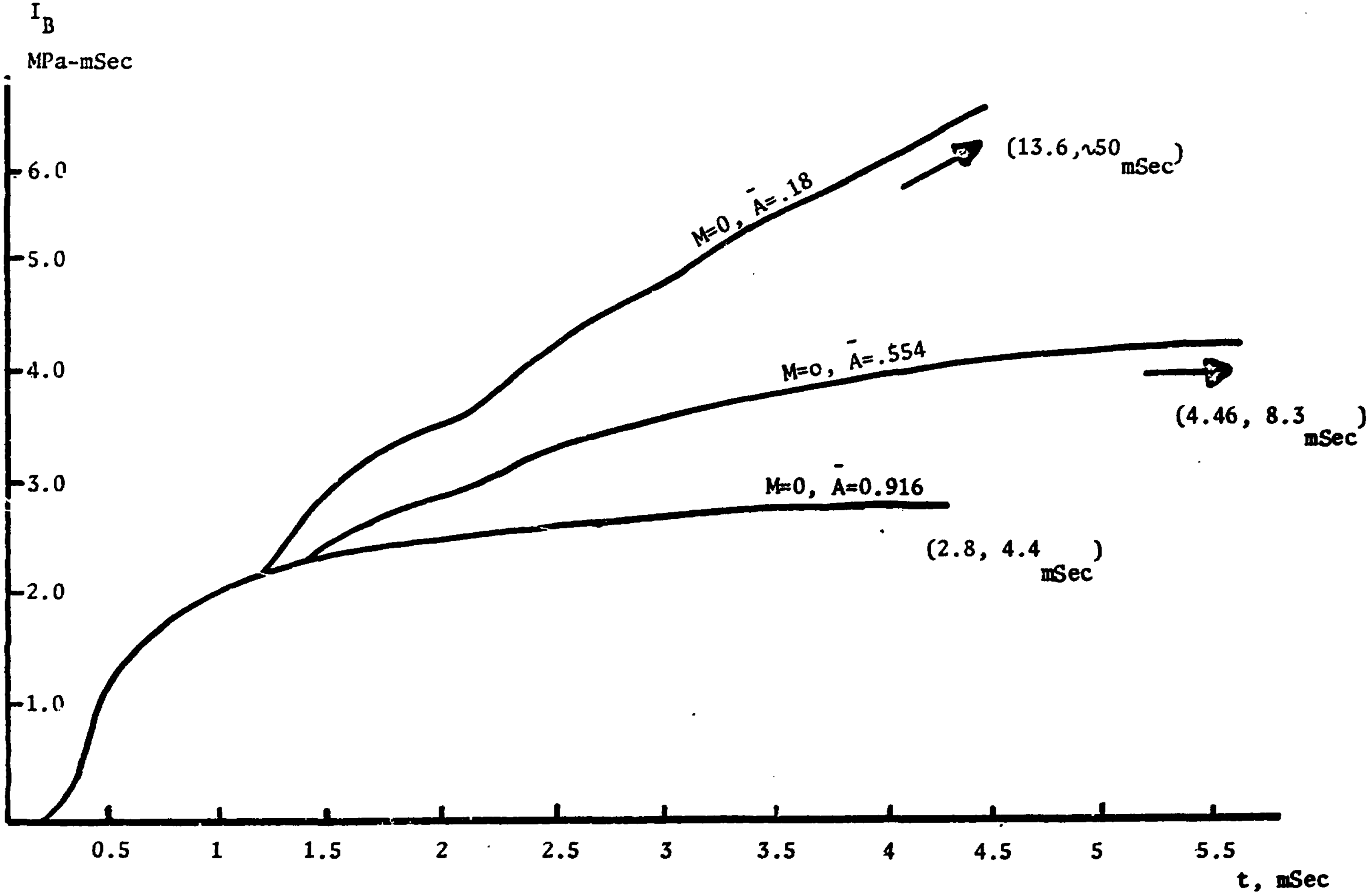

Fig. 4a: Backwall Impulse

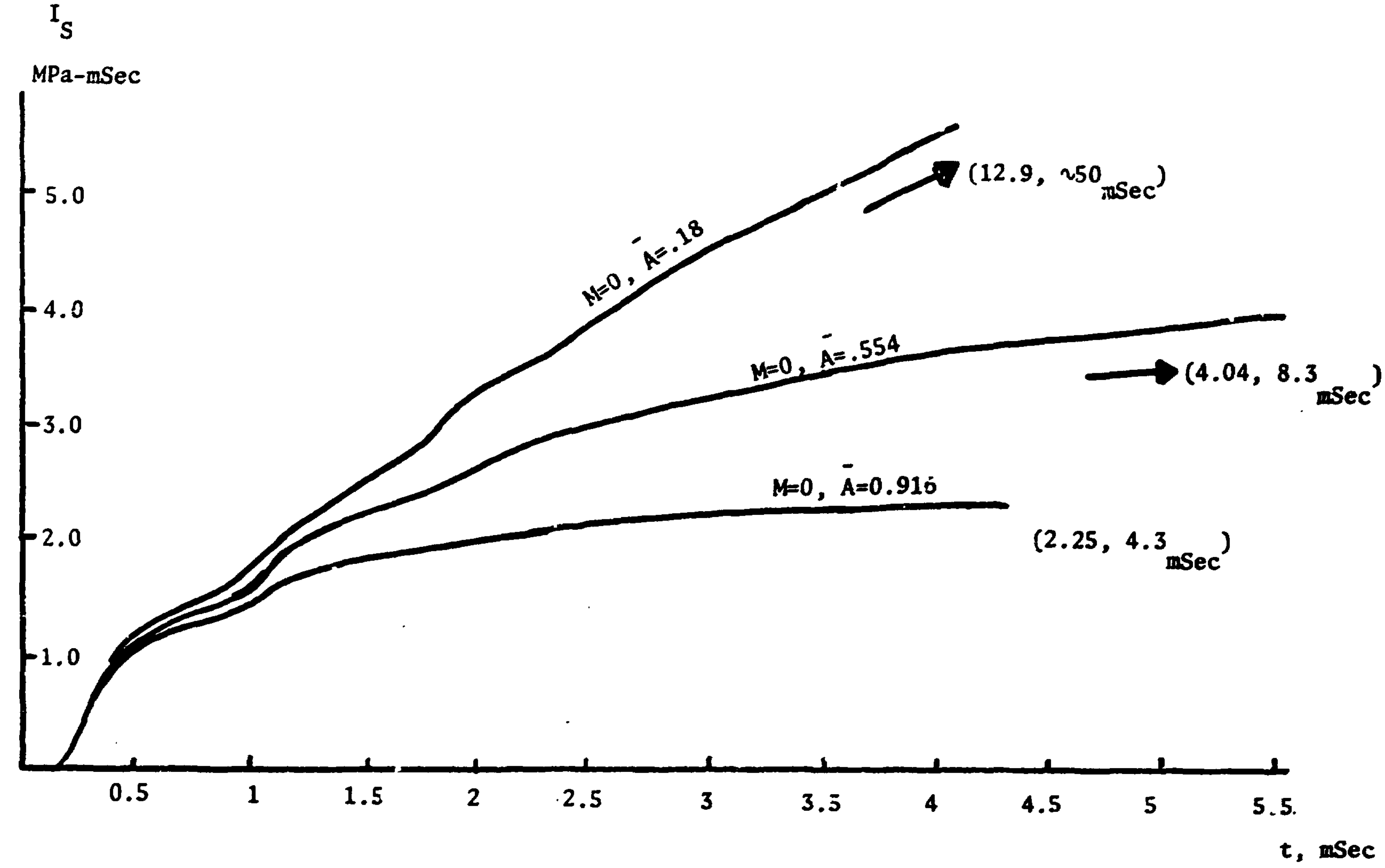

Fig. 4b: Sidewall Impulse

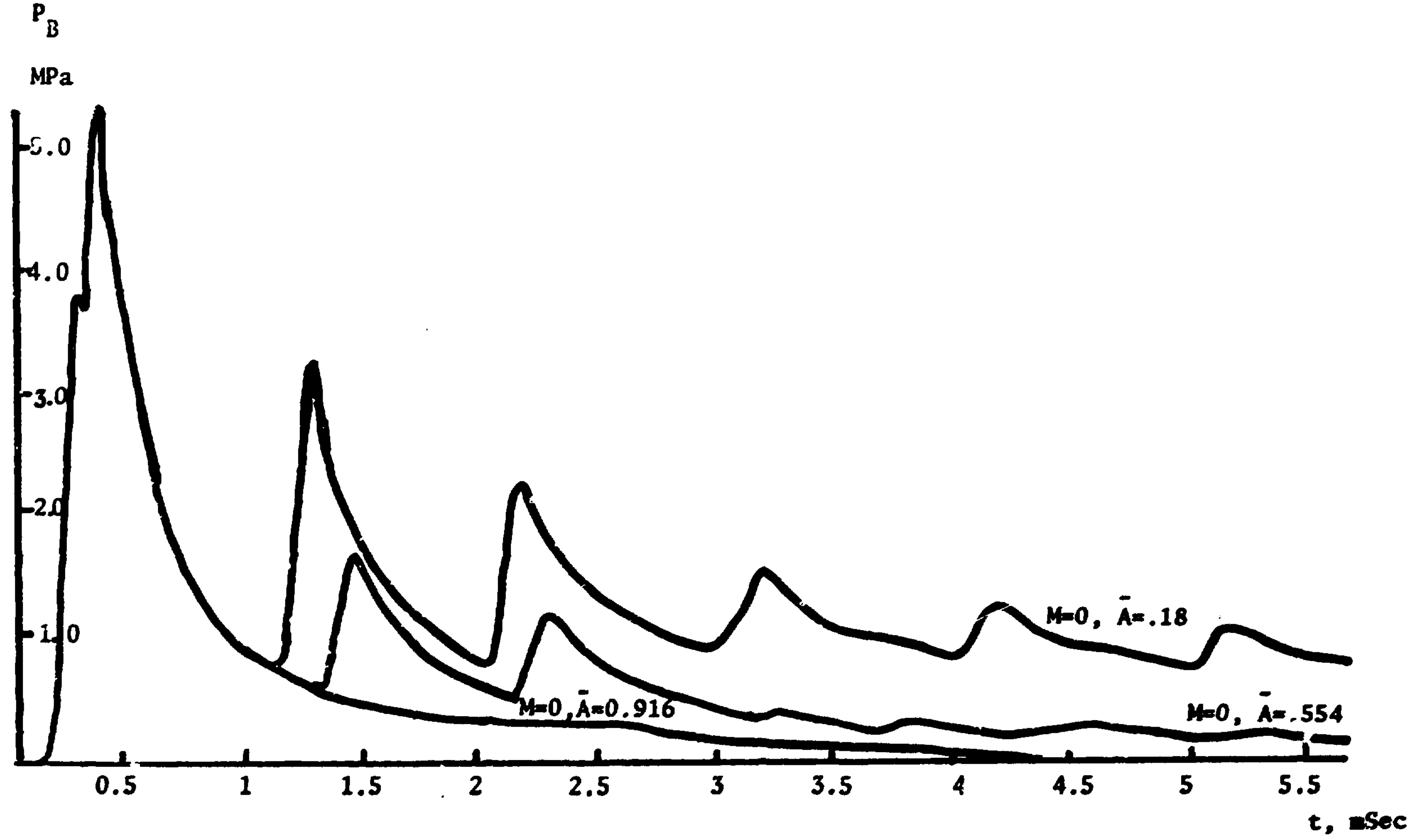

Fig 5a: Backwall Average Pressure

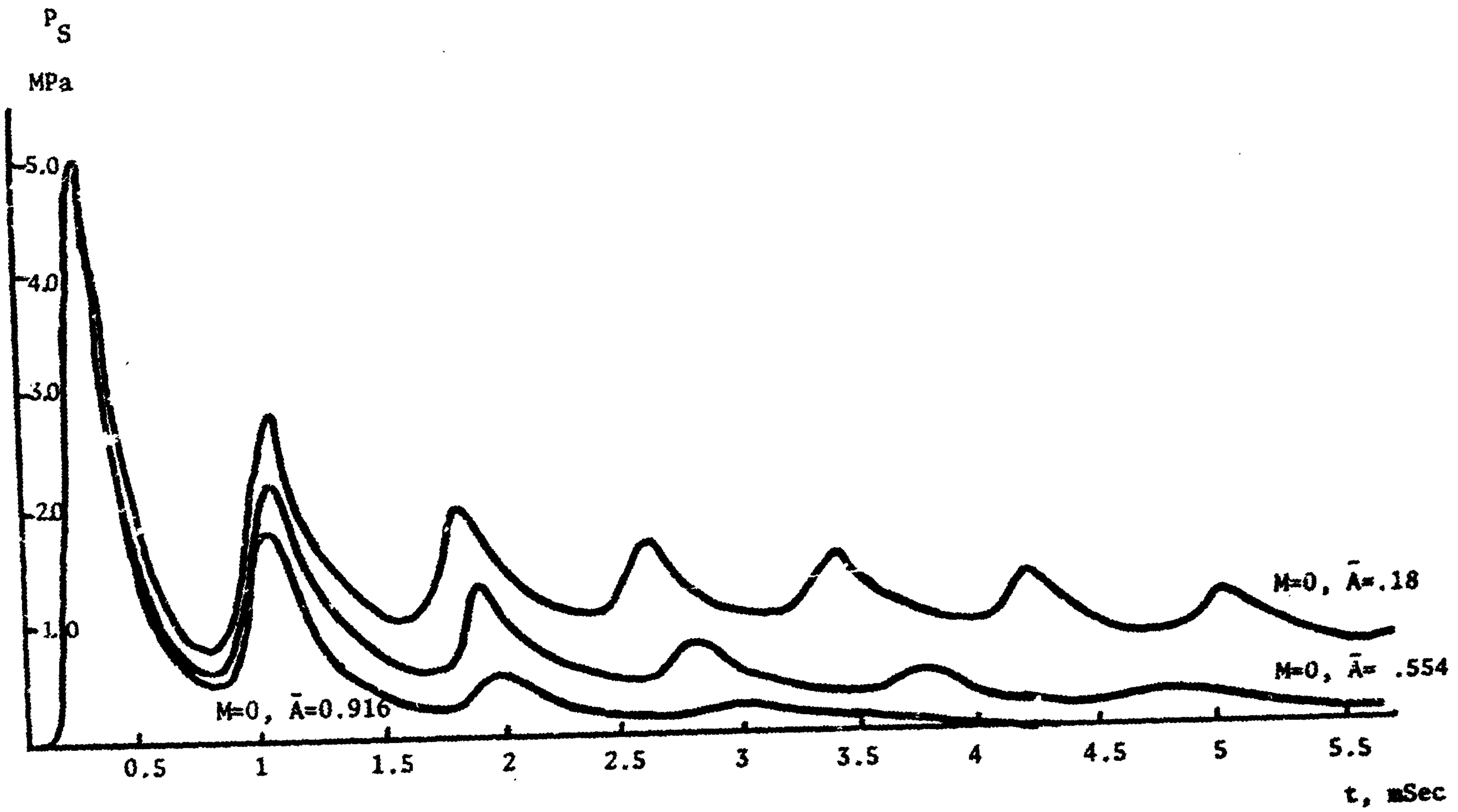

Fig. 5b: Sidewall Average Pressure

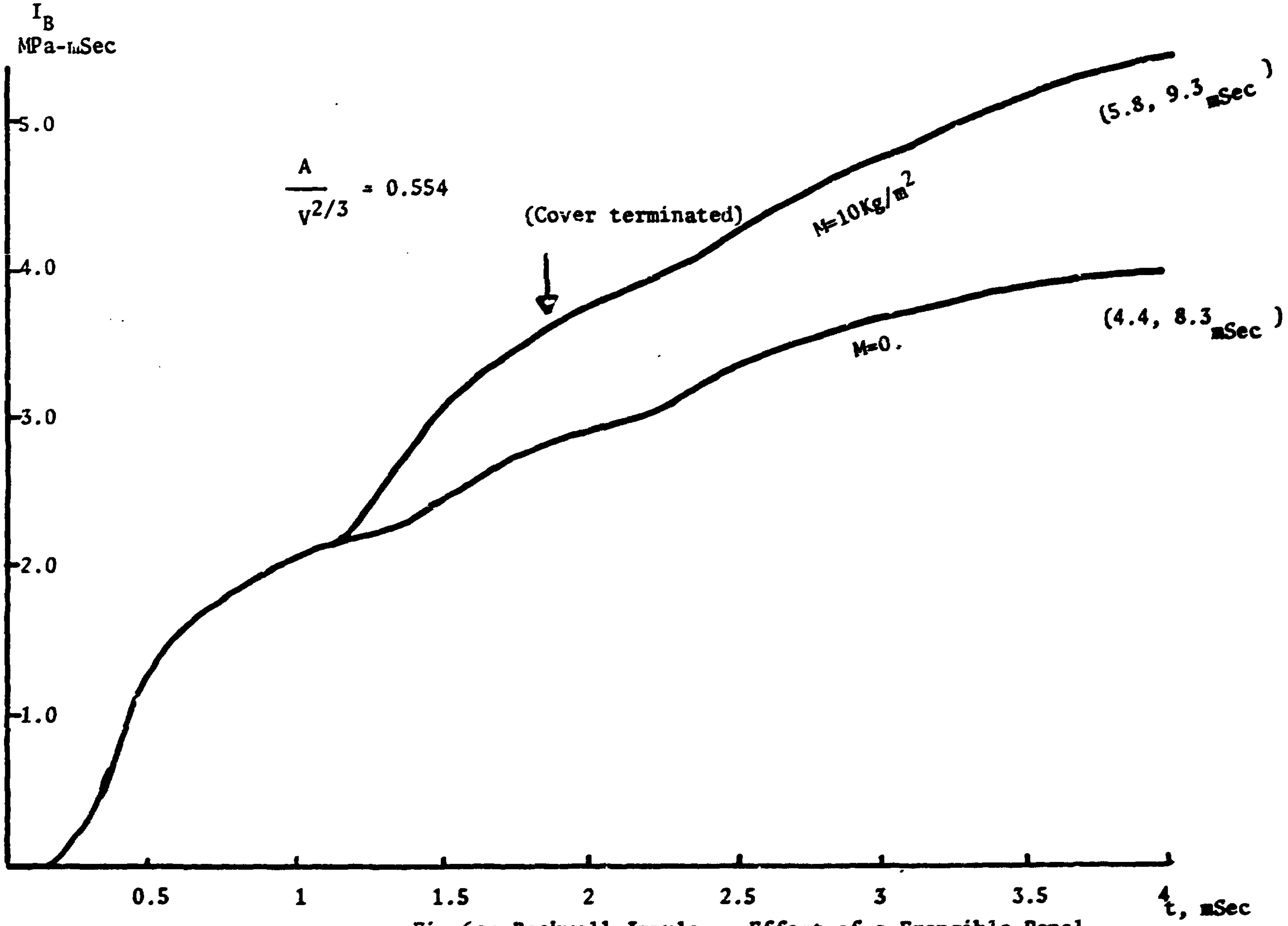

Fig 6a: Backwall Impulse - Effect of a Frangible Panel

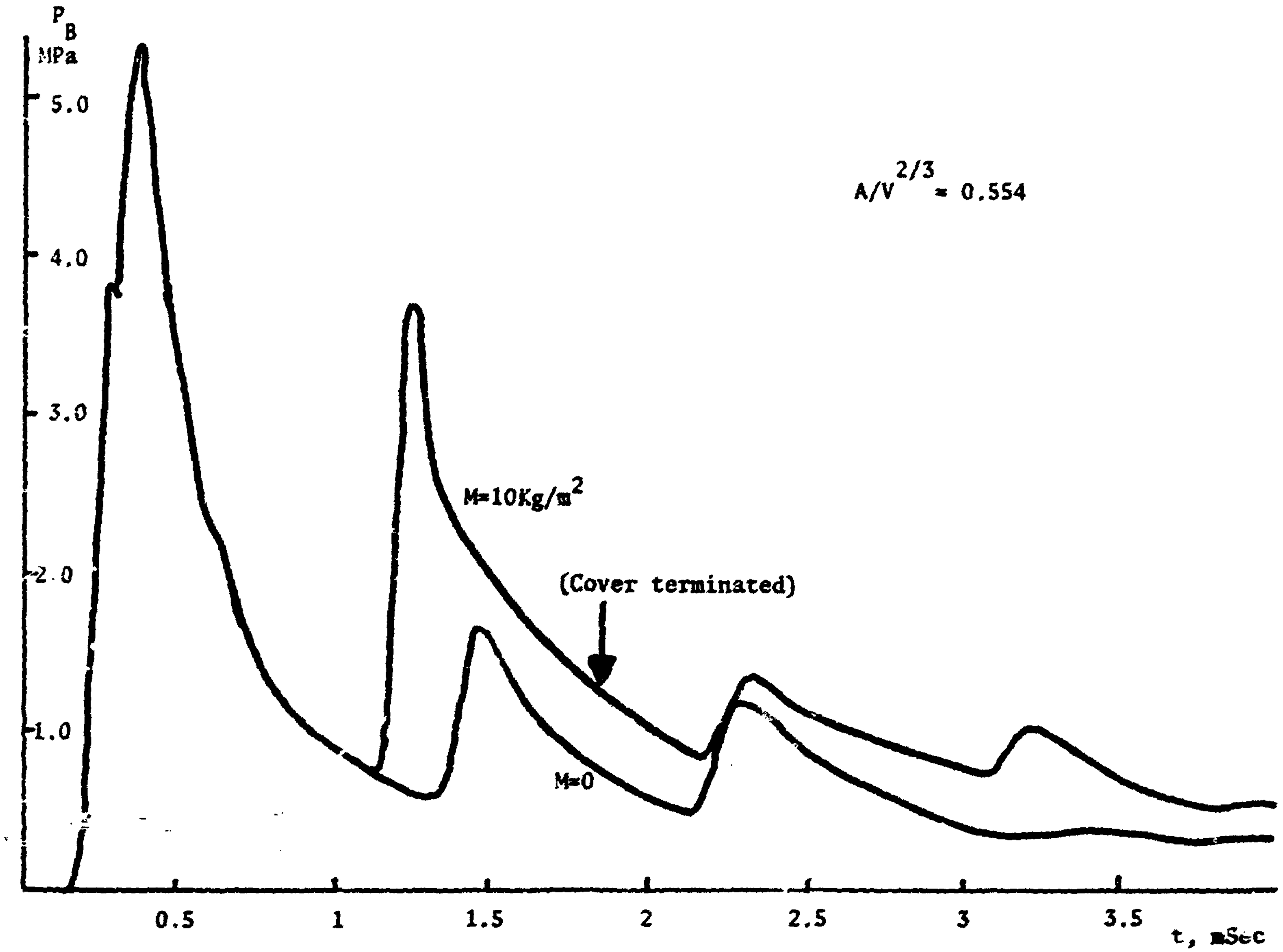

Fig 6b: Backwall Average Pressure - Effect of a Frangible Panel

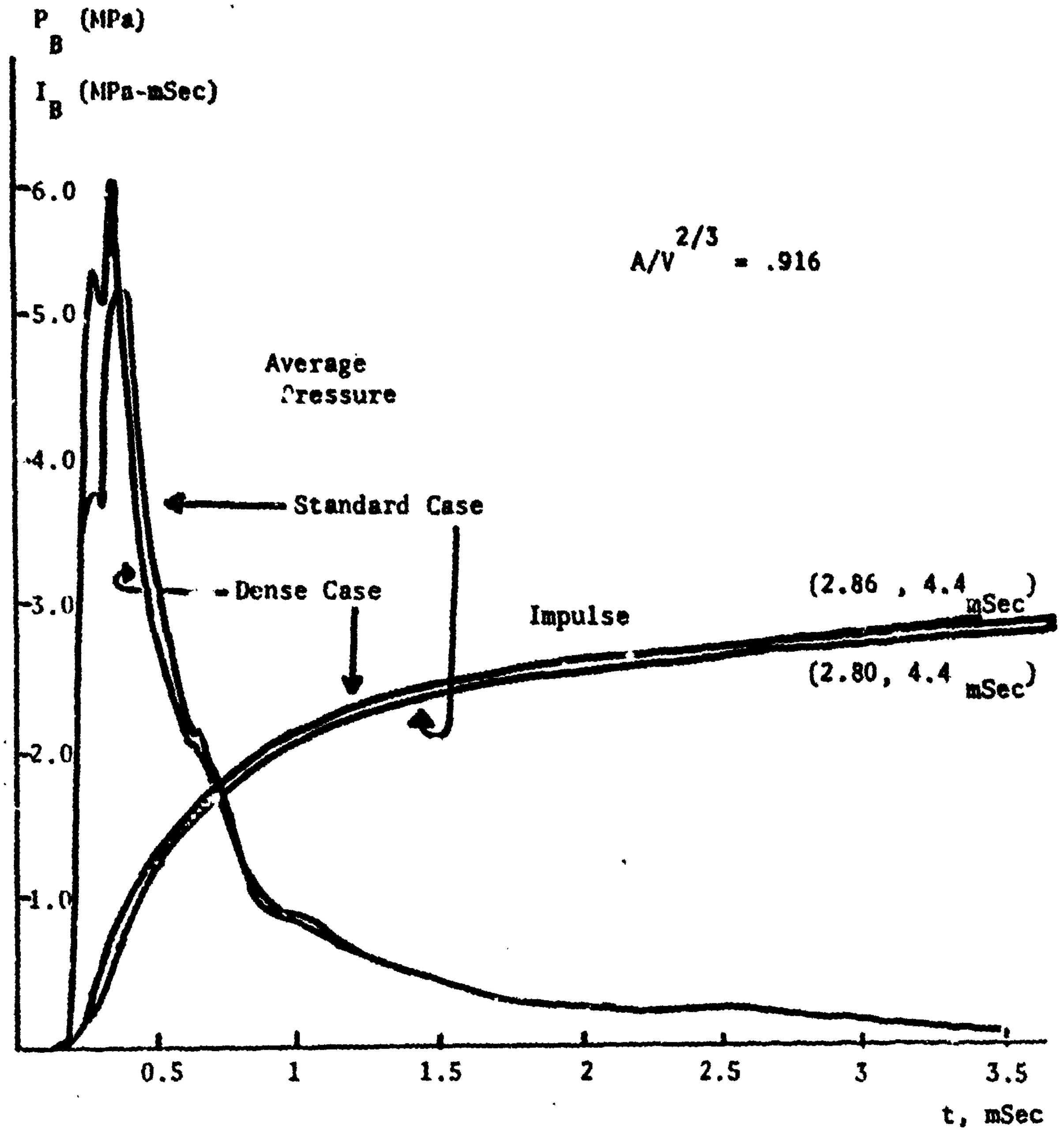

Fig 7a: Backwall Impulse and Average Pressure - Effect of Energy Density

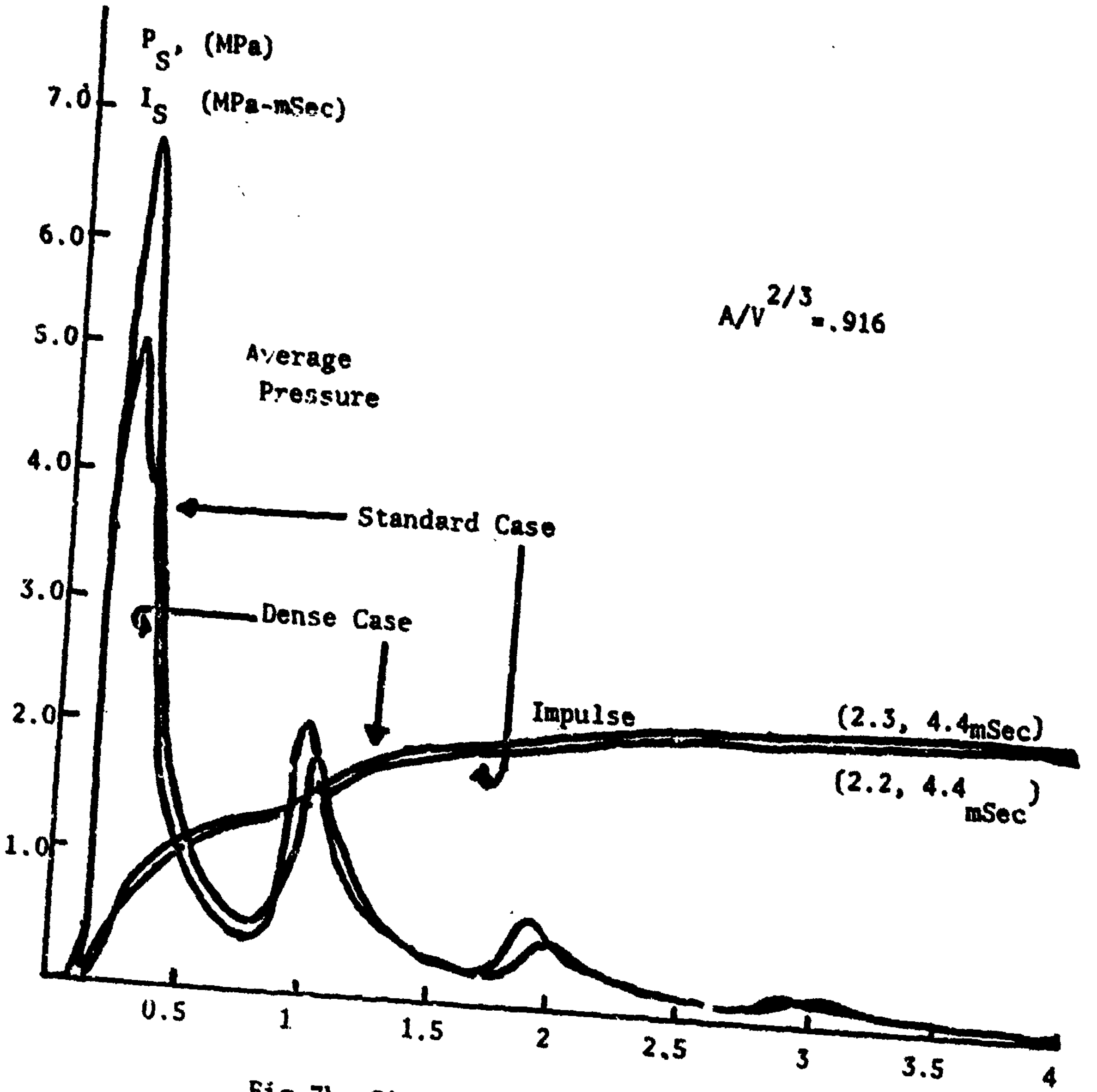

Fig 7b: Sidewall Impulse and Average Pressure - Effect of Energy Density

PRESSURE/TEMPERATURE DECAY IN AN EXPLOSION CONTAINMENT ROOM

by

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INTRODUCTION

The U.S. Army Corps of Engineers is designing chemical demilitarization facilities to reduce the number of stockpiled chemical weapons. In the demil process, weapons are mechanically sheared inside an explosion containment room (ECR). This reinforced concrete room is designed to provide complete blast and fragment confinement and contain the release of chemical agent in the event of an accidental explosion (Figure 1). This paper describes a study conducted by Southwest Research Institute to determine the post-explosion environment (pressure/temperature decay) inside an ECR following an accidental explosion of chemical munitions.

An estimate of the post-explosion pressure and temperature decay is needed to evaluate potential hazards from

- cookoff of munitions inside the ECR
- leakage of toxic gas through cracks in the walls and penetrations
- required time to return to a safe temperature
- spontaneous combustion of materials inside the ECR

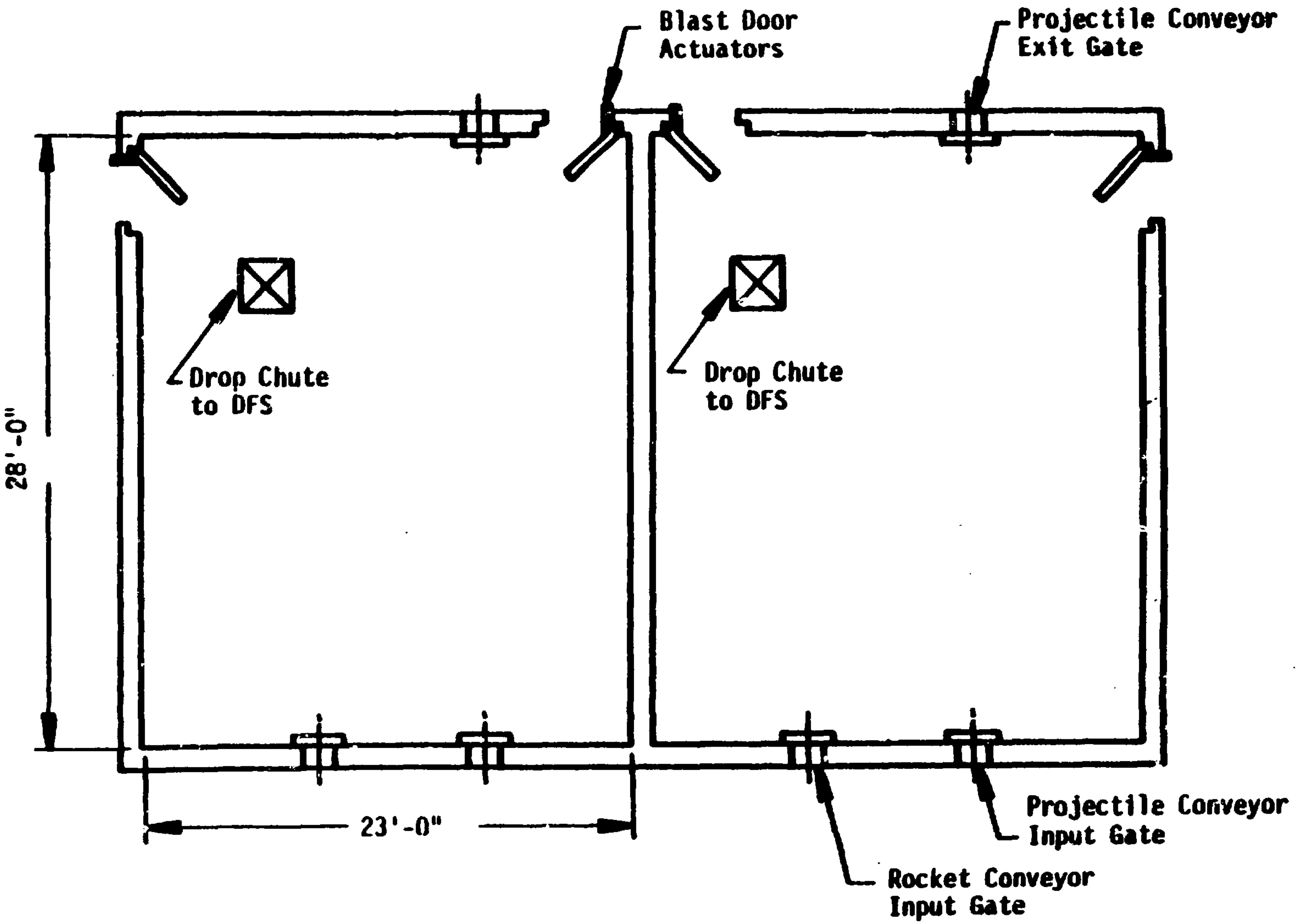


Figure 1. JACADS ECR Floor Plan

The study was performed in three stages. First, the post-explosion environment inside the containment room was studied by experimentally observing the cooldown phenomenon in a modeled test cell. A heat transfer analysis was then performed to predict a temperature decay that could be compared to experimental data. Complete confinement (no leakage) was assumed in the analysis. Finally, the problem was evaluated numerically to model simultaneously heat dissipation and gas leakage.

EXPERIMENTAL STUDY

An experimental program of 13 tests was performed to examine the transient temperature and pressure in an unvented enclosure following an HE explosion [1]. A 55 gram spherical charge of Comp B was detonated inside an 80 cu ft steel structure. Blast and gas pressures, thermal flux, and temperatures were recorded.

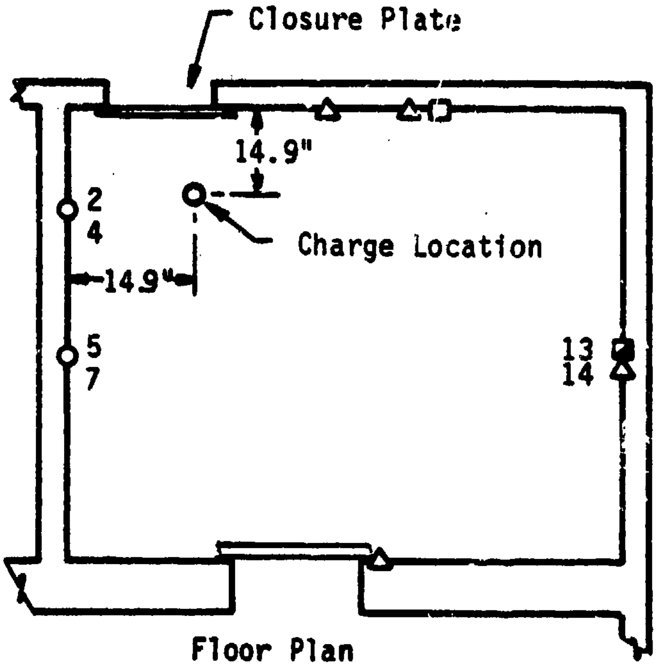
The test cell was approximately a one-fifth scale model of the ECR (based on geometric scaling). The primary objective of the test program was to study blast pressures inside the structure. Hopkinson scaling was then used instead of thermal scaling. However, we felt that test data could also be collected on thermal transients in the chamber and utilized in the analysis. It was thought that a heat transfer analysis capable of predicting the cooldown in the test cell should also predict cooldown in the ECR.

The test cell differed from the ECR in that it was constructed of steel rather than concrete and that there were no blast doors or penetration panels. Pneumatic tests made before and after the testing showed the cell remained virtually leak tight during the test sequence.

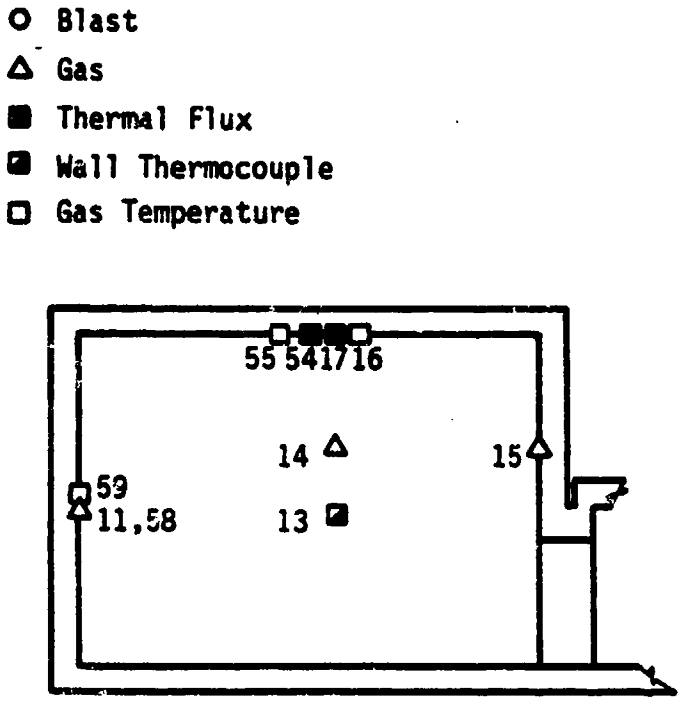
The instrumentation locations in the test chamber are shown in Figure 2. Four blast and gas pressure sensors, two gas temperature sensors, two wall temperature sensors, and two heat flux sensors were placed in the test cell.

Figure 3 illustrates the pressure decay in the test cell following an explosion. Pressure fluctuations caused by the reflection of shocks in the

Gage Locations Inside Test Chamber



Floor Plan



Side View

Figure 2. Gage Locations Inside Test Chamber

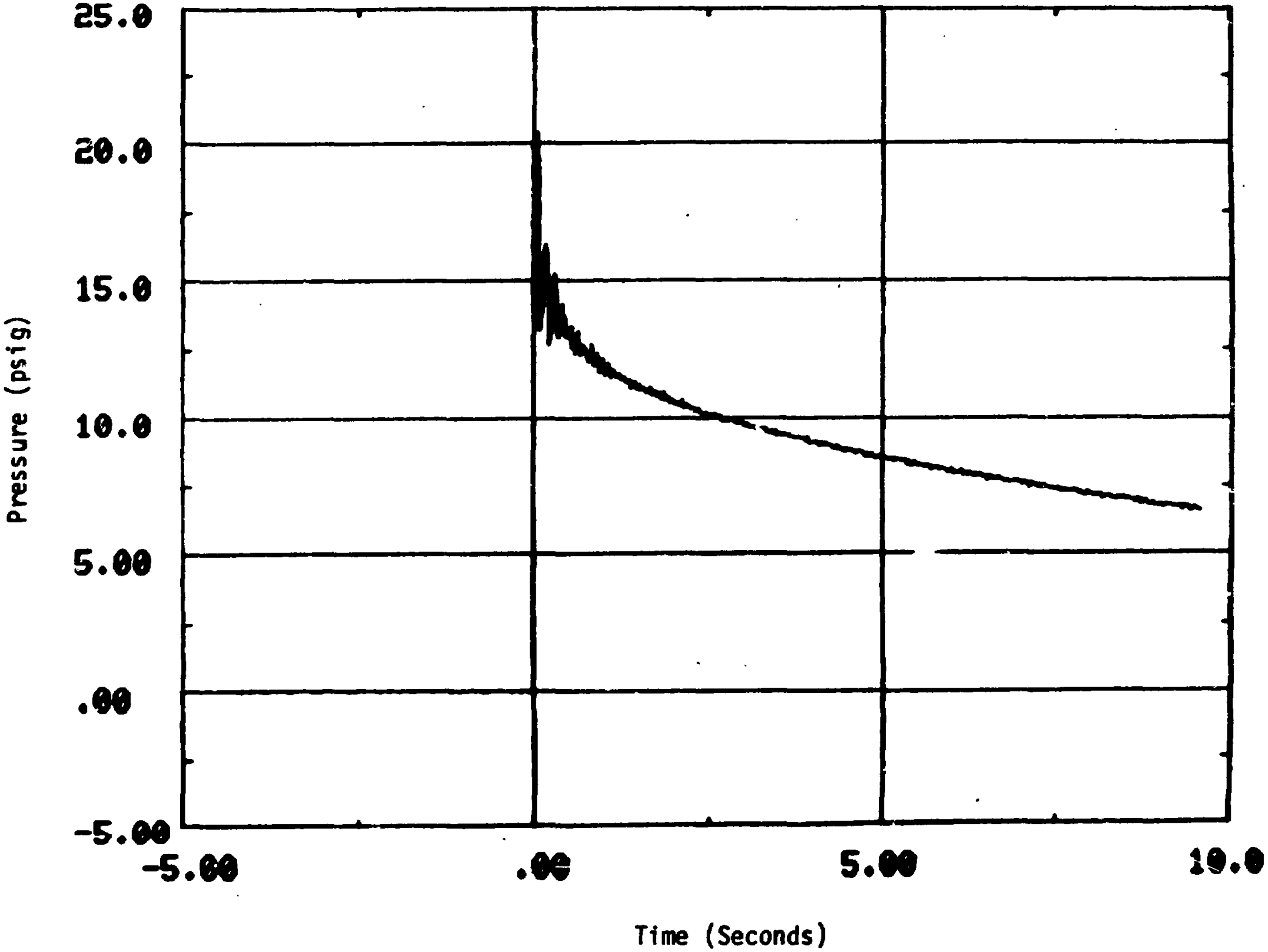


Figure 3. Post Detonation Pressure Inside the Test Chamber

cell die down within a second of the detonation. During the first second, the gas pressure decays rapidly, but later slows to an exponential decay.

Thermal measurements show that the wall temperature and heat flux reach a maximum at about 0.1 seconds after the detonation and quickly (within 0.5 seconds) diminish to a fraction of the peak value (Figure 4). Following an initial peak of about 130°F, the wall surface temperature remains within 15°F of the ambient temperature during the duration of the cooldown.

The experimental results reveal two distinct phases of gas cooldown. Immediately after the detonation, thermal radiation is the dominant heat transport mechanism as the hot gas products rapidly release heat to the surroundings. As the gases inside the ECR are explosively set in motion with the detonation, heat transfer is enhanced by forced convection. This effect is short lived; however, as the gases are randomly tossed about, no steady flow fields are established.

The second phase of cooldown is characterized by a slower rate of temperature decay. Heat is lost by natural convection as buoyancy effects induce flow paths between hot and cool regions. The diffusion of heat from the interior of the room to the walls is the rate determining process. The walls are able to conduct away from the surface as quickly as it is applied. This is evidenced by the near ambient wall surface temperatures observed in the experiment.

HEAT TRANSFER ANALYSIS

The objective of the heat transfer analysis [2] was to develop a prediction procedure based on the dominant heat transfer mechanism during the cooldown, natural convection.

The gross cooldown of the gas inside the enclosure may be simplified to the following energy transfer.

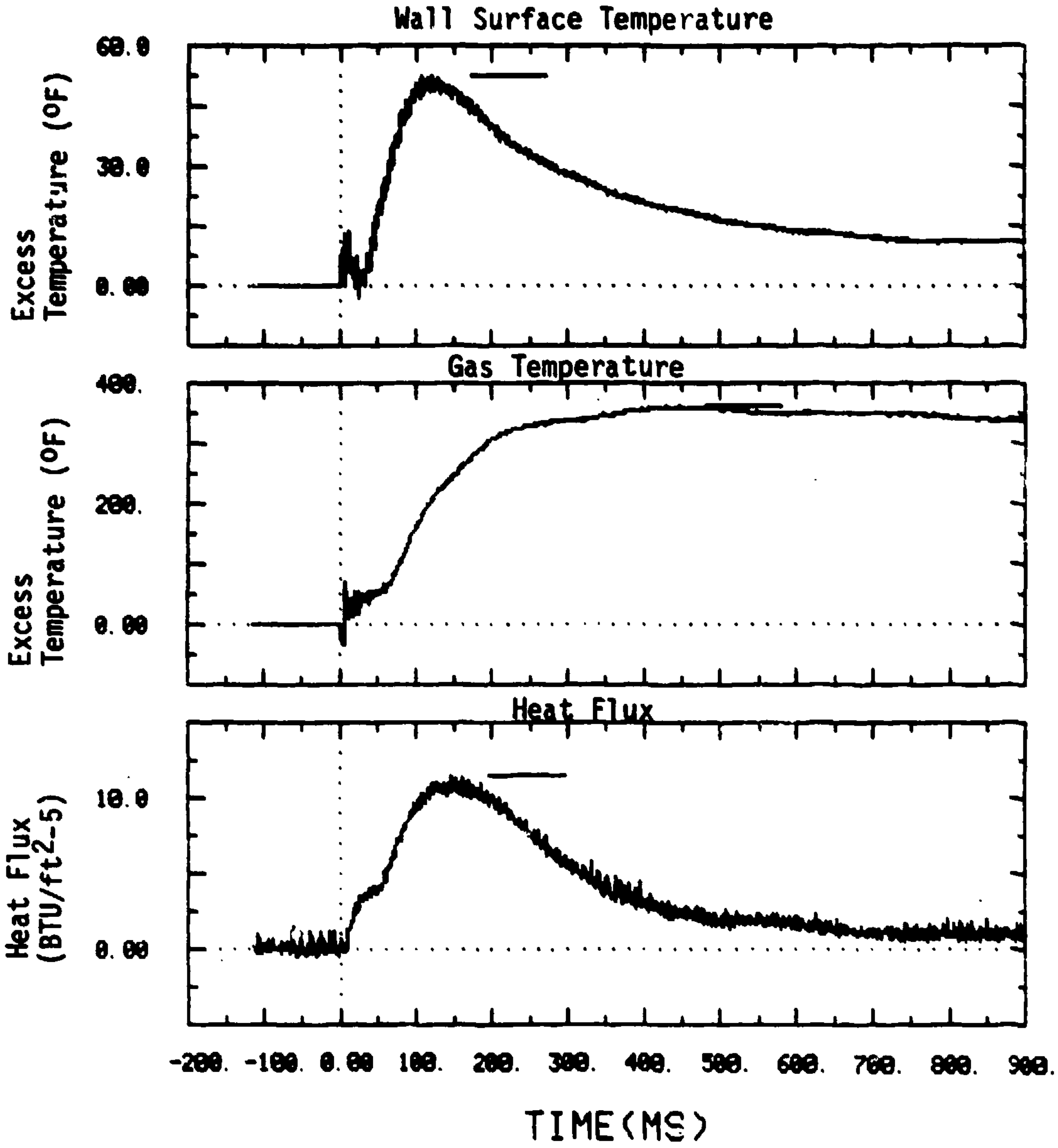


Figure 4. Thermal Measurements Inside Test Cell

$$\begin{pmatrix}\text{rate of decrease in}\\ \text{internal energy}\end{pmatrix} = \begin{pmatrix}\text{convective heat flow}\\ \text{to surroundings}\end{pmatrix}$$

$$\rho c_v V \frac{dT}{dt} = -hA(T-T_w) \qquad (1)$$

where V and A are the volume and surface area of the room, ρ, c_p, and h are the density, constant volume specific heat, and convective heat transfer coefficient of the gas; T, and T_w are the gas and wall temperatures; and t is the time.

The solution to the differential equation is

$$\frac{T - T_w}{T_{qs} - T_w} = \mathrm{EXP}\left(\frac{-hAt}{\rho c_v V}\right) \qquad (2)$$

where T_{qs} is the peak gas temperature.

Assumptions made in this simplification are:

- radiation is neglected. The first phase of cooldown is ignored to give a conservative (longer duration) prediction.
- wall temperature remains constant.
- complete gas mixing from the explosively driven turbulence of the detonation.
- ideal gas behavior. This permits a correlation between temperature and pressure; $T-T_w/T_{qs}-T_w = \dot{P}/P_{qs}$.
- gas properties based on time weighted gas temperature.

The convective heat transfer coefficient is dependent on the properties of the gas (kinematic viscosity, thermal diffusivity, etc.) and on the geometric constraints on the convective flows in the enclosure. Natural convection is defined in nondimensional terms. The Rayleigh number, Ra, is the ratio of the buoyant and viscous forces in the gas, and so corresponds to the amount of gas motion in the enclosure. The Nusselt number, Nu, is the ratio of the amount of heat transfer from convection and conduction. The Nusselt and Rayleigh numbers have been related empirically for a variety of geometries. The cooldown was examined by considering the enclosure as vertical or horizontal plates, and as a vertical cylinder.

An eight-step procedure is used to predict the temperature/pressure decay:

1. The peak quasi-static pressure, P_{qs}, is determined for the ratio of charge weight to room volume.

2. The total number of moles of gas in the enclosure following the detonation (including combustion products) is determined.

3. The peak quasi-static temperature, T_{qs}, is estimated from the ideal gas law.

4. A time-weighted temperature, T*, and film temperature, Tm, are calculated based on an exponential decay. Gas properties are evaluated at the film temperature.

5. The Rayleigh number is determined at temperature T*.

6. The Nusselt number is found as a function of the Rayleigh number.
   $Nu = c\ Ra^b$
   where b and c are empirical constants.

7. A convective heat transfer coefficient is determined from the Nusselt number.

8. The pressure-temperature decay is taken from Equation 2.

Comparisons of predicted to experimentally observed transient pressure are shown in Figure 5. The predicted decay rate, m, closely estimates the experimental data when the theoretical calculations are based on an average of vertical/horizontal plate configurations. This heat transfer model may then be applied with some confidence to the cooldown inside the ECR.

NUMERICAL ANALYSIS

In the chemical demil process, sections of munitions sheared apart in the ECR are dropped through a feed chute to a furnace retort (Figure 1). A structural analysis of the feed chute leading from the ECR to the deactivation furnace [3] reported potential plastic deformation in the chute should an accidental explosion occur. This blast-induced deformation creates a gap in the containment room through which gases would leak through. A numerical analysis [4] was required to consider simultaneous gas leakage and cooldown. Gas leakage rates and the effect of leakage on the pressure decay were determined.

The governing equation was modified to include leakage by

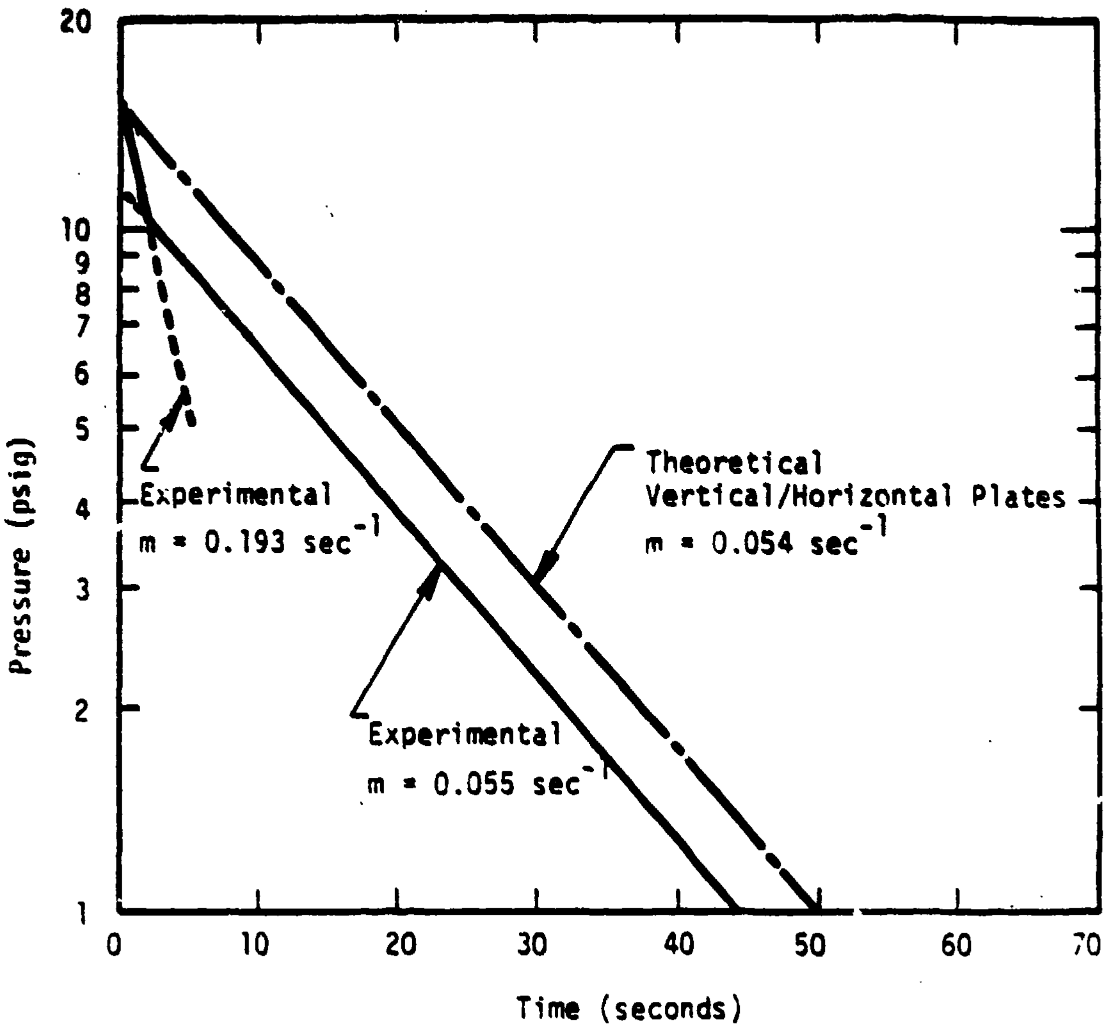
$$\left\{\begin{matrix}\text{rate of decrease in}\\ \text{internal energy}\end{matrix}\right\} = \left\{\begin{matrix}\text{heat loss to}\\ \text{leaking gas}\end{matrix}\right\} + \left\{\begin{matrix}\text{convective heat flow}\\ \text{to surroundings}\end{matrix}\right\}$$

$$\rho c_v V \frac{dT}{dt} = -\dot{m}_\ell c_p T - hA(T-T_w)$$

where $\dot{m}_\ell$ is the leakage rate and c_p is the constant pressure specific heat of air. The leakage mass flow of a compressible ideal gas through an orifice is

$$\dot{m}_\ell = C_D A_\ell \sqrt{2 P_\rho \left(\frac{\gamma}{\gamma-1}\right)\left[\left(\frac{P_e}{P}\right)^{\frac{2}{\gamma}} - \left(\frac{P_e}{P}\right)^{\frac{\gamma-1}{\gamma}}\right]} \quad \text{for unchoked flow}$$

$$\dot{m}_\ell = C_D A_\ell \sqrt{\gamma P_\rho \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \quad \text{for choked flow}$$



$$\frac{T - T_W}{T_{QS} - T_W} = \frac{P}{P_{QS}} = EXP\ (-mt)$$

where $m = \frac{hA}{\rho c_v V}$

Figure 5. Predicted Vs. Experimental Transient Pressures in the Test Chamber

where C_D is a discharge coefficient, A_ℓ is the leak area, γ is the ratio of specific heats (C_p/C_v), and P_e is the environment pressure. These equations were solved simultaneously with a Runge-Kutta numerical integration computer program.

Diffusion of heat into the concrete ECR walls was numerically analyzed as a finely divided series of lumped nodes. Results show surface temperatures remain close to ambient as the heat of the gas is quickly absorbed by the massive walls. At depths greater than one inch into the concrete, no noticeable change in temperature (greater than 1°F) was computed. The thermal response of the walls surrounding the enclosed explosion is then essentially the same for concrete or steel.

A sample of the results of the computer simulation is shown in Figure 6. The pressure response of the ECR is highly dependent upon the leakage rate. For the leakage area considered, for example, the depressurization caused by cooldown in neglectable relative to the leakage.

CONCLUSIONS

The cooldown following an HE explosion in an explosion containment room was investigated. The post explosion temperature/pressure environment was analyzed. The three-part study was comprised of: experimental modeling, heat transfer analysis, and numerical modeling of cooldown with gas leakage.

Two phases of cooldown were observed. Radiant heat flow and explosively driven, forced convection in the first fraction of a second result in a rapid temperature and pressure decay. At later times, natural convection dominates and the pressure decays exponentially.

The transient pressure/temperature decay was modeled based on the natural convection in the enclosure evaluated at a time-weighted temperature. Predicted values compared closely to experimental data.

A numerical simulation was developed to determine the impact of leakage on the pressure and temperature inside the enclosure during cooldown.

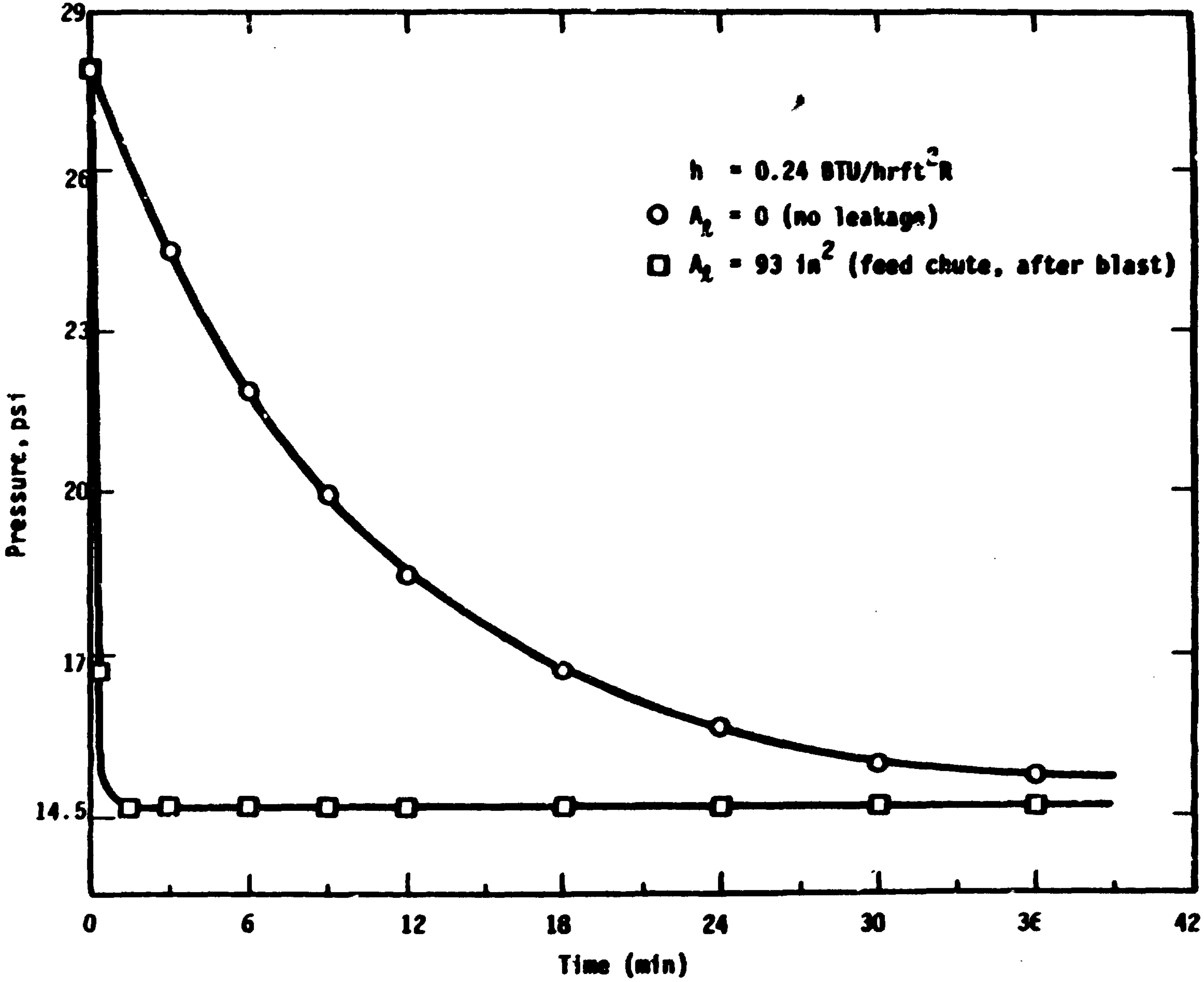


Figure 6. Depressurization in the ECR With and Without Leakage

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CONTENTS OF STRUCTURES TO RESIST THE EFFECTS OF ACCIDENTAL EXPLOSIONS (TM 5-1300, NAVFAC P-397, AFM 88-22)

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ABSTRACT

Procedures for structures designed to resist the effects of HE type explosions are presently available in the Tri-Service Design Manual Structures to Resist the Effects of Accidental Explosions (TM 5-1300, NAVFAC P-397, AFM 88-22). However, these procedures are limited to reinforced concrete structures. Since its original publication, a considerable amount of data has been generated which brought about the requirement to revise existing procedures in the manual and incorporate new data. This describes the differences between the old and new manual and discusses the additional data incorporated in the new manual.

CONTENTS OF
STRUCTURES TO RESIST THE EFFECTS OF ACCIDENTAL EXPLOSIONS
(TM 5-1300, NAVFAC P-397, AFM 88-22)

INTRODUCTION

This paper summarizes the material contained in the design manual Structures to Resist the Effects of Accidental Explosions. This manual, as contained in Reference 1, shall here after be referred to as the "new manual". The present 1969 publication of the "Tri-Service Manual", as contained in Reference 2, shall here after be referred to as the "old manual".

Subsequent to the publication of the old manual, various government agencies conducted several high explosive tests. These tests were perfomed to determine explosive environments, and the response of specific structures and materials. The result of these tests have provided sufficient additional information to revise the H. E. Protection Design Criteria of the old manual.

VOLUME I - INTRODUCTION

Volume I consists of an expanded discussion of the topics in Chapters 1 to 3 of the old manual. The specific global topics are illustrated in Figure 2. The significance of the new manual can be seen in its expanded discussion and treatment of the topics concerned with the safety factor, explosive protection systems, and design tolerances.

Although the factor of safety remains unchanged between the old and new manuals, the new manual contains a discussion of the effects of increasing the flexural strength of a member beyond the design requirements, and the detrimental effect this has on supporting members.

The three components of explosive protection systems are described in detail. Namely, Donor, Protection and Acceptor Systems, are discussed independently and interdependently. The aim of the discussion is to enable the Designer to judge the requirements of each portion of the explosive system, to produce a practical and cost effective system.

The old manual considered three pressure design ranges. The new manual considers only close-in and far-out ranges. However, these two design ranges consider the pressure-time variation rather than the pressure alone on both the acceptor system and the protective structure.

Lastly, the extensive increase in the data pertaining to acceptor sensitivity has been included in the new manual. Specifically, human tolerance to both blast pressure and shock, explosive initiation by fragments, and equipment tolerances to shock loads, are discussed. Knowledge of acceptor sensitivity is an important factor in developing practical and cost effective protective structures.

VOLUME II - BLAST, FRAGMENT AND SHOCK LOADS

This volume is presented in three main sections, as is shown in Figure 3. The first section is concerned with protective structures sustaining the impact of a blast load pressure due to an explosion. The second section is concerned with primary and secondary fragments associated with the break-up of a explosive charge casings, equipment, or buildings containing an explosion. The third section is concerned with the motions induced in protective structures due to an impact with the shock front and/or ground motions due to an explosion.

BLAST LOADS:

A summary of the changes and additions presented in the new manual compared to the old manual is illustrated in Figure 4. Based on recently developed data, the major change in the free air burst curves are the modification of the impulse curves (both incident and reflected waves), and the positive duration of the shock wave, as may be seen in Figure 5.

On the other hand, the magnitude of the blast pressures acting on the ground due to an air burst are completely different, as is shown in Figure 6. Furthermore, the new manual contains impulse loads corresponding to the new peak pressures acting at various locations on the ground, as is shown in Figure 7.

Blast parameters associated with a surface burst explosion of TNT have not changed. However, additional blast parameters for 95 different explosives other than TNT, also detonated on ground (surface burst), have been included. These additional explosives vary in explosive and casing material and shape. An example of this data is shown in Figure 8.

Blast loads from vented explosions refer to those detonations which occur next to a barricade or other obstruction, or within a cubicle type structure, which permits total venting of the explosive effects. The impulse loads associated with close-in detonations presented in the new manual differ from those of the old manual because they are based on new data obtained after the publication of the old manual. Specifically, the new manual contains revised average peak impulse loads, and additionally, the newly developed associated average peak pressures. These average pressures are used in conjunction with the average impulses to define the internal shock loads of a cubicle type structure, as is shown in Figure 9.

Previous data presented for vented explosions assumed that light material panels at one or more sides of a structure would permit total venting. Recent test data has indicated that even light material panels will permit reflections, increasing shock loads within a cubicle. The new manual presents this new data, and defines the magnitude of the internal loads and the pressures venting out of a structure with light material panels.

Blast loads corresponding to confined explosions are similar to those of vented explosions except for the additional long duration loading which occurs within the fully contained structure. These latter additional loads are referred to as quasistatic or gas pressure loads, and are produced by the accumulation of the gaseous products of detonation and the increase in temperature within the fully confining structure. The magnitude of gas pressures presented in the new manual may be seen in Figure 10. In addition, the new manual gives the impulse of this gas pressure load for various charge weight to structure volume ratios. Scaled impulse as a function of scaled vent area is given for various weights of vent covers. A sample of these curves is shown in Figure 11.

The procedures for determining blast loads acting on the exterior of rectangular shelter type structures were available in the old manual. These procedures have been refined and supplemented in the new manual to more closely define the blast environment for a shock front impinging on a shelter not only orthogonally, but at an angle, as illustrated in Figures 12 and 13. In addition to the blast loads acting on the exterior surfaces of a structure, the new manual presents procedures to determine the internal environment due to the leakage of external blast pressures into a structure through openings, as is illustrated in Figure 14.

FRAGMENTS:

Fragment generations from explosions consist of primary fragments formed by the fragmentation of explosive casings or containers, and secondary fragments formed by the break-up of equipment located in the general vicinity of the explosion. Procedures for primary fragments was presented in the old manual. However, the procedure was limited to only cylinderically shaped explosive casings. The new manual has expanded the procedure to contain non-cylinderical containers as well.

The damage caused by secondary fragments is a function of the size and shape, the attained velocities, and the direction of propogation of the missiles. The new manual contains procedures to evaluate all these parameters, as is shown in Figure 15.

SHOCK LOADS:

Blast loads acting on a structure and/or transmitted through the ground to a structure, cause motions in a structure. This motion causes the vibration of internal objects (such as ceilings, walls, equipment, etc.). If the structure or the internal objects are not designed to sustain the shock loads, failure can occur.

Structure motions produced by a shock load due to a detonation can be classified in three categories. The first being the motions due to a direct impact of an air blast. The second being motions produced by an air blast acting on the ground surface. The third being the ground shock effects due to the transmission of the shock wave directly through the ground. The first category generally causes the most severe motions.

The new manual presents procedures to determine the three categories of structure motion. These procedures are summarized in Figure 16. The procedure for determining motions due to a direct air blast impact utilize numeric integration. After determining the air blast loads acting on a structure, a rigid body analysis is performed with consideration for the resisting friction between the structure and the ground. The procedures for the other two categories are based on empirical relationships, established from tests.

After determining the structure motions, shock response spectras may be evaluated to establish the structure shock environment. These shock spectras are to be used to respectively design the structural components.

VOLUME III - PRINCIPLES OF DYNAMIC ANALYSIS

This volume contains the procedures for analyzing structural elements subjected to blast overpressures. The procedures and charts are general and apply to reinforced concrete and structural steel as well as to other materials whose dynamic structural strength can be expressed. The outline of the contents of the volume is listed in Figure 17.

The procedures for determining the resistance-deflection functions have been significantly increased in the new manual. The old manual contained the elastic, elasto-plastic and ultimate resistances and stiffnesses of several one-way and symmetrically supported and reinforced two-way members. The new manual considers additional one-way members with various load and support conditions. The two-way members considered have been increased to include unsymmetrically supported and/or reinforced (if concrete) elements. However, as was the case in the old manual, the elements are for uniform load conditions.

As in the old manual, the new manual utilizes the single-degree-of-freedom method to represent the motions of the actual structure subjected to blast loads. The utilization of the single-degree-of-freedom method requires determining the load, the mass, the resistance, the load factor, the mass factor or as an alternative the load-mass factor. Transformation factors are presented for one way members having variable loadings while load-mass factors are presented for various two-way spanning elements.

The present manual contains two response charts for idealized triangular pressure-time loads. One chart pertains to maximum structure response while the second is used to determine rebound loads. The number of response charts furnished in the new manual has been increased to 216. These new charts cover the maximum elastic response to triangular, rectangular loads, gradually applied loads, triangular pulse loads and sinusoidal loadings. The new charts also cover the maximum resonse of elasto-plastic systems to trangular loads, rectangular loads, gradually applied loads, triangular pulse loads and bilinear-triangular loads. The bilinear-triangular load condition (Figure 18) represents the idealized pressure-time load which would occur in a partially vented structure. Figure 19 illustrates the response curves for bilinear-triangular loads.

In addition to the expanded section on response charts, the new manual contains procedures for performing numerical integration as a means of analyses. These analyses include both the average-acceleration-method as well as the acceleration-impulse-extrapolation-method. Procedures are presented which include damping in a system as well as for analyzing two-degree-of-freedom systems.

VOLUME IV - REINFORCED CONCRETE DESIGN

The technical data in the volume for the design of concrete structures has been greatly expanded from the previous edition (Figure 20). Not only has the existing data been expanded, a considerable amount of new data has been added. This additional data will facilitate the design of more cost effective struct [illegible] eliminating conservativeness resulting from a lack of data.

The old manual is concerned primarily with the design of laced reinforced concrete walls to resist the effects of close-in detonations. Some data is included for the design of slabs to resist the blast effects of far range explosions. A well informed individual could adapt and expand this considerable amount of data to enable the not so informed individual to prepare realistic and cost effective designs.

The new manual provides a better estimate of the dynamic capacity of both the concrete and reinforcing steel than the old manual. Based on recent research and testing, the dynamic increase factors for both concrete and reinforcing steel are presented as a function of the actual resonse of the structural elements as well as the values needed for design. In addition, the static yield strength of the reinforcement is increased 10 percent beyond the minimum specified by the ASTM to account for the actual strength steel that is furnished by the steel producers. Finally, the shear capacity of concrete elements as presented in the current manual has proved to be conservative. Therefore, the new manual deletes the capacity reduction factor applied to the shear capacity of concrete.

Conventionally reinforced (unlaced) concrete elements were not extensively treated in the old manual. Only a limited amount of data was presented for the design of one- and two-way elements. This new manual greatly expands this data to include design procedures for slabs and walls of various support conditions, as well as design procedures and deflection criteria for beams and both interior and exterior columns. The design of slabs include not only one- and two-way slabs of various support conditions, but also includes the design of flat slabs. Also, when support conditions permit, tension membrane action of the slabs is incorporated in the design. The inclusion of this membrance action permits the slab to attain relatively large deflections at reduced strength and thereby resulting in substantial cost savings.

The design for close-in blast effects is concerned solely with the design of laced concrete elements in the old manual. Laced concrete walls can be designed for deflections ranging from small to larger to incipient failure conditions and beyond to the design of post-failure fragments. Unlaced concrete walls may also be designed for close-in effects. However, these walls must contain shear reinforcement in the form of single leg stirrups (Figure 21) and the scaled distance between the wall and explosive charge must be greater than 1.0 to prevent breaching of the wall. The charge may be located considerably closer for laced walls.

The relationship between the design parameters for unlaced one- and two-way slabs or panels is illustrated in Figure 22. An element may be designed to attain deflections corresponding to support rotations up to 2 degrees under flexural action (Figure 23). For far range effects, stirrups would be provided if the shear capacity of the concrete is not sufficient to develop the ultimate flexural strength. A Type I cross-section provides the ultimate moment capacity. The flexural action of the element may be increased to 4 degrees support rotation if single leg stirrups are provided to restrain the compression reinforcement. In this deflection range, a Type II cross-section provides the ultimate moment capacity and mass to resist motion. For close-in effects, the element must utilize stirrups. A minimum quantity of stirrups is required even if the shear capacity of the concrete is sufficient to develop the ultimate flexural capacity. The maximum permissible deflection of the element would be limited to 4 degrees support rotation. If spalling occurs, a Type III cross-section provides the ultimate moment capacity.

A non-laced element may be designed to attain large deflections, that is, deflections corresponding to 8 degrees support rotation. These increased deflections are possible only under tension membrance action (Figure 24). The element must have sufficient lateral restraint to develop in-plane forces. For close-in effects stirrups are required, while for far range effects, stirrups would be provided only if the shear capacity of the concrete is strength of the element. A Type III cross-section provides the ultimate moment capacity and mass to resist motion.

Flat slab structures are designed to resist the blast and fragments associated with a far range explosion. The relationship between the design parameters for flat slabs is illustrated in Figure 25. Flat slabs may be designed to attain limited or large deflections in the same manner as non-laced elements. Under flexural action alone, the slab may attain deflections corresponding to 2 degrees support rotation. The flexural action may be extended to 4 degrees rotation if single leg stirrups are added to restrain the flexural reinforcement. If sufficient continuous flexural reinforcement is provide, the slab may attain 8 degrees support rotation through tension membrane action. Unless necessary for shear, single leg stirrups are not required for the slab to achieve tension membrane action.

The design of beams as presented in the new manual apply to beams in shear wall type structures rather than rigid frame structures. The design procedure presented is for transverse loads only. Axial loads are not considered. However, the procedure includes the design for torsion. The relation between the design parameters for beams is illustrated in Figure 26. The design of beams is similar to the design of one-way slabs.

Beams are generally employed in structures designed to resist the effects associated with far range explosions. They may be designed to attain limited or large deflections in the same manner as non-laced slabs. Under flexural action alone, a beam may attain 4 degrees support rotation and, if sufficient lateral restraint is provided, the beam may attain 8 degrees support rotation under tension membrane action. Closed stirrups are always required for beams. While usually not the case, beams may be designed to resist close-in explosions. They could generally be employed as pilasters around door openings.

The design of columns is limited to those in shear wall type structures where the lateral loads are transmitted through the floor and roof slabs to the exterior (and interior, if required) shear walls. Due to the extreme stiffness of the shear walls, there is negligible sidesway in the interior columns and, hence, no induced moments due to lateral loads. Therefore, interior columns are axially loaded members not subjected to the effects of lateral load. However, significant moments can result from unsymmetrical loading conditions.

Design procedures are included for both tied and spiral columns. Slenderness effects are included in the procedures. Exterior columns of shear wall type structures are generally designed as beams.

The structural design for brittle mode response contains most of the data from the previous manual. However, prediction curves for the occurrence of spalling of concrete is included. These curves will more realistically predict the need for costly structural steel spall plates. In addition, the structural behavior to primary and secondary fragment impact is expanded.

The new edition of the manual contains a chapter on foundation design. The data presented will enable the Designer to predict the gross motion of structures subject to overturning. The structure motion is based on rigid body motion to predict soil-structure interaction.

The last portion of this volume greatly expands the detailing procedures presently incorporated in the manual. The old manual provides details for laced construction. These details are expanded to include information provided for conventionally reinforced concrete, elements incorporating either single leg stirrups or lacing, flat slabs, beams, columns and foundations.

VOLUME V - STRUCTURAL STEEL DESIGN

This volume covers detailed procedures and design techniques for the blast-resistant design of steel elements and structures subjected to short-duration, high-intensity blast loading. Highlights of this volume are presented in Figure 27.

While the design techniques presented in the old manual are applicable to single-degree-of-freedom, elasto-plastic systems, there was no clear-cut method for determining the properties of a structural steel element, such as moment capacity, resistance, allowable or ultimate stresses, dynamic increase factors equivalent stiffness, etc., that are relevant to such a system. This volume covers the methods as they apply to beam-type and plate-type systems.

The effects of rapidly applied dynamic loads on the mechanical properties of structural steel are considered. Figure 28 illustrates the dynamic increase factors for yield stresses at various strain rates.

The design procedures and applications of this volume are directed toward steel acceptor- and donor-type structures. Donor-type structures, which are located in the immediate vicinity of the detonation may include steel containment cells or steel components of reinforced concrete containment structures such as blast doors or closure plates. In some cases, the use of suppressive shielding to control or confine the hazardous blast, fragment and flame effects of detonations may be an economically feasible alternative. The high blast pressures encountered in these suggest the use of large plates or built-up sections with relatively high resistance. In some instances, fragment impact or pressure leakage must be considered. Acceptor-type structures are removed from the immediate vicinity of the detonation. These include typical frame structures with beams, columns and beam-columns composed of standard structural shapes and built-up sections. In many cases, the relatively low blast pressures suggest the use of standard building components such as open-web joists, prefabricated wall panels and roof decking detailed as required to carry the full magnitude of the dynamic loads. Another economical application can be the use of entire pre-engineered buildings, strengthened locally, to adapt their designs to low-blast pressures (up to 2 psi) with short duration.

Beam-type elements differ from plate-type in that the effects of overall and local instability upon the ultimate capacity is an important consideration. The design of these elements, including beams, beam-columns, open-web joists, and cold-formed panels, in which slenderness effects are prominent, are covered in this volume. In general, the ultimate resistance of a beam-type system is reduced in light of local or overall instability. Plate-type elements, in which local or overall instability is not predominant, are covered in much the same way as their reinforced concrete counterparts. Special requirements for blast doors, with respect to their function during and after an explosion, are discussed (Figure 29).

The procedures for the design of structural systems, involving a multi-degree-of-freedom analysis are presented. Preliminary designs for rigid frames and braced frames subjected to blast loads are presented. Methods for proportioning the frame members for maximum economy are considered. Figure 30 illustrates such proportioning by way of collapse mechanisms, for rigid frames. Computer programs, which cover the elasto-plastic dynamic analysis of framed structures, are available for final design.

Some qualitative differences between steel and concrete protective structures warrant special consideration for rebound, stress-interaction, connection integrity and fragments.

(1) The amount of rebound in concrete structures is considerably reduced by internal damping (cracking) and is essentially eliminated in cases where large deformations or incipient failure are permitted to occur. In structural steel, however, a larger response in rebound, up to 100 percent, can be obtained for a combination of short duration load and a relatively flexible element. As a result, steel structures require that special provisions be made to account for extreme responses of comparable magnitude in both directions.

(2) The treatment of stress interaction is more of a consideration in steel shapes since each element of the cross-section must be considered subject to a state of combined stresses. In reinforced concrete, the provision of separate steel reinforcement for flexure, shear and torsion enables the designer to consider these stresses as being carried by more or less independent systems.

(3) Special care must be taken in steel design to provide for connection integrity up to the point of maximum response. For example, in order to avoid premature brittle fracture in welded connections, the welding characteristics of the particular grade of steel must be considered and the introduction of any stress concentrations or notches at the joint must be avoided.

(4) If fragments are involved, care should be given to brittle modes of failure as they affect construction methods. For example, fragment penetration depth may govern the thickness of a steel plate.

VOLUME VI - SPECIAL CONSIDERATIONS IN EXPLOSIVE FACILITY DESIGN

The contents of this volume is new and was not presented in the old manual. This volume is divided into nine subsections, as is shown in Figure 31.

All of the above subsections are independent of each other, and could have been presented in separate volumes. However, their short length, and in some cases their function as introductions to specific manuals in which their topics are completely discussed, made their combination into one volume more desirable.

MASONRY DESIGN:

This subsection describes the procedures for designing a masonry wall subjected to blast overpressures. The design procedures consider free standing masonry walls; masonry walls working in conjunction with structural steel frames, as illustrated in Figure 32; and arch action in masonry walls, permitting the design of walls for large deflections. In addition, this subsection also includes an outline of the design criteria and the dynamic strength of materials to be used for blast resistant designs.

PRECAST CONCRETE DESIGN:

This subsection includes procedures for the design of precast concrete elements subjected to blast overpressures. A method for determining the ultimate strength of a precast element from the static and dynamic material strengths is presented. Methods for performing a dynamic analysis and determining rebound loads are presented. Also presented are recommended details for precast construction, as is shown in Figure 33.

PRE-ENGINEERED BUILDINGS:

Standard pre-engineered buildings are usually designed for conventional loads such as dead, live, snow, and wind loads. Blast resistant pre-engineered buildings must be designed in a similar manner, but with much higher static loads to account for the actual blast loads. This subsection presents methods for the design of the foundation, the metal frame, and the roofing and siding of a pre-engineered building. It includes a method for performing a blast analysis of such a structure. It also includes a recommended specification for pre-engineered buildings subjected to blast overpressures.

SUPPRESSIVE SHIELDING:

This subsection summarizes the design and construction procedures which are outlined in the design manual Suppressive Shields - Structural Design and Analysis Handbook (HNDM 1110-1-2). As is shown in Figure 34, only those shields which have received safety approval have been presented. Also presented are procedures with which new shields may be analyzed and designed. In addition, included are recommended details for penetrations, such as utility and vacuum lines and personnel and equipment doors, along with other required structural details to obtain safety approval.

BLAST RESISTANT WINDOWS:

Historically, explosion effects have produced airborne glass fragments from failed windows at the risk to life and property. Based on a series of explosive tests, guidelines have been developed for the design, evaluation, and certification of windows to safely survive a prescribed blast environment. This subsection contains design criteria for both glazing and frames. In addition, the presented design procedures include a series of design charts, as is shown in Figure 35, as well as construction details.

DESIGN LOADS FOR UNDERGROUND STRUCTURES:

This subsection contains a summary of the data presented in the design manual Fundamentals of Protective Design for Conventional Weapons (TM5-855-1). The data pertaining primarily to the effects of an explosion occurring on or below the ground, and the blast pressures produced on below ground structures, is presented. Also procedures are presented for bomb penetration into earth, as well as for the structural design of below ground walls and roof slabs.

EARTH-COVERED ARCH-TYPE MAGAZINES:

This subsection deals with typical earth covered magazines which are used for the storage of explosives. It is an expansion of a similar section in the old manual, and includes requirements for both metal and reinforced concrete arch magazines (as is shown in Figure 36), including semi-circular and oval shapes. A discussion of the method of design, required safe separation distance between magazines, and construction procedures is also included

BLAST VALVES:

This subsection discusses remote and blast actuated blast valves used for sealing ventilation openings in protective structures. Included is a discussion of the requirements of plenums and fragment protection. Also included is a list of manufacturers and a description of the valves, their pressure capacities, closure times, flow rates, and test data if available. In addition, a recommended specification for poppet valves is included.

SHOCK ISOLATION SYSTEMS:

The data for Shock Isolation Systems presented in this subsection is greatly expanded from that presented in the old manual. The new manual data is basically qualitative rather than quantitative. It includes shock tolerances for personnel and equipment; shock isolation principles; methods of analyzing isolation systems; shock isolation arrangements, including individual and group mounting platform characteristics; isolator arrangements, consisting of base and overhead mounted systems (see Figure 37); and shock isolation devices, such as helical coil, torsion, pneumatic, liquid, and other spring configurations.

STRUCTURES TO RESIST THE EFFECTS OF ACCIDENTAL EXPLOSIONS
(TM 5-1300, NAVFAC P-397, AFM 88-22)

MANUAL CONTENTS

VOLUME I - INTRODUCTION
VOLUME II - BLAST, FRAGMENT AND SHOCK LOADS
VOLUME III - PRINCIPLES OF DYNAMIC ANALYSIS
VOLUME IV - REINFORCED CONCRETE DESIGN
VOLUME V - STRUCTURAL STEEL DESIGN
VOLUME VI - SPECIAL CONSIDERATIONS IN EXPLOSIVE FACILITY DESIGN

COMPUTER PROGRAM REPOSITORIES

FIGURE 1

VOLUME I
INTRODUCTION

GENERAL INTRODUCTION	BACKGROUND, MANUAL SCOPE & FORMAT
SAFETY FACTOR	SAFETY FACTOR APPLICATION
EXPLOSION PROTECTION SYSTEM	DEFINITION OF COMPONENT (DONOR SYSTEM, ACCEPTOR SYSTEM, PROTECTIVE STRUCTURES, ETC.)
DESIGN TOLERANCES	DEFINITION OF DESIGN RANGES, PROTECTION CATEGORIES HUMAN TOLERANCES, EQUIPMENT TOLERANCES, EXPLOSIVE SENSITIVITY

FIGURE 2

VOLUME II

BLAST, FRAGMENT AND SHOCK LOADS

BLAST LOADS	1.	UNCONFINED EXPLOSIONS
	2.	VENTED EXPLOSIONS
	3.	CONFINED EXPLOSIONS
FRAGMENTS	1.	PRIMARY FRAGMENTS - EXPLOSIVE CASING OR CONTAINERS
	2.	SECONDARY FRAGMENTS - CAUSED BY EQUIPMENT BREAKUP
SHOCK LOADS	1.	GROUND MOTION - AIR AND GROUND INDUCED
	2.	AIR BLAST MOTIONS - SLIDING
	3.	SHOCK SPECTRA

FIGURE 3

SUMMARY OF MODIFICATIONS OF BLAST LOADS PRODUCED BY TNT

CHARGE CONFINEMENT	CATEGORY	PRESSURE LOAD	MANUAL		REMARKS
			OLD	NEW	
UNCONFINED EXPLOSION	FREE AIR BURST	UNREFLECTED	X	X	MODIFIED
	AIR BURST	REFLECTED	X	X	MODIFIED
	SURFACE BURST	REFLECTED	X	X	UNMODIFIED
CONFINED EXPLOSION	FULLY VENTED	INTERNAL SHOCK	X	X	MODIFIED
		LEAKAGE	X	X	MODIFIED
	PARTIALLY CONFINED	INTERNAL SHOCK	X	X	MODIFIED
		INTERNAL GAS		X	ADDED
		LEAKAGE		X	ADDED
	FULLY CONFINED	INTERNAL SHOCK	X	X	MODIFIED
		INTERNAL GAS	X	X	MODIFIED

FIGURE 4

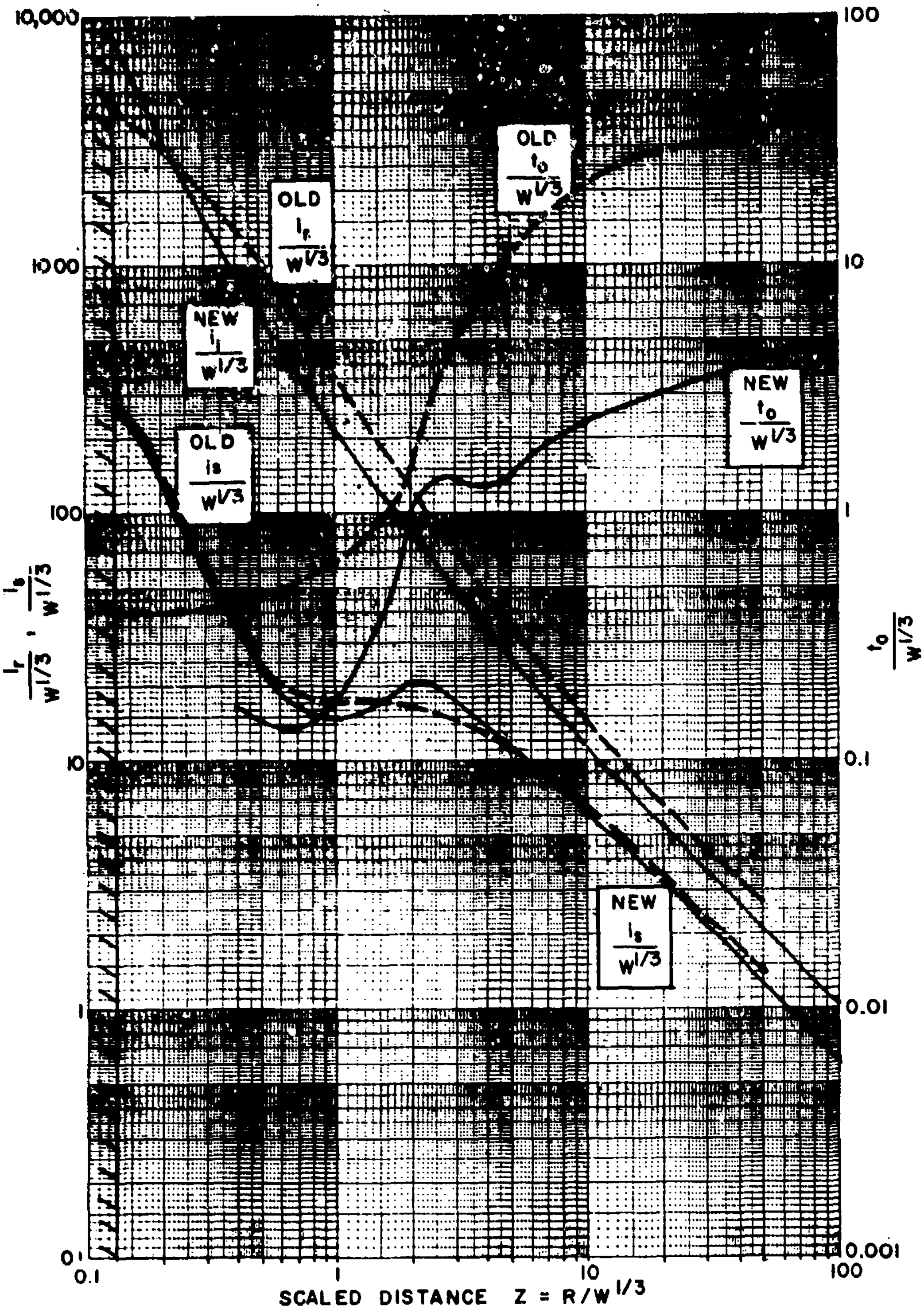


FIGURE 5 MODIFICATION OF FREE AIR BURST CURVES

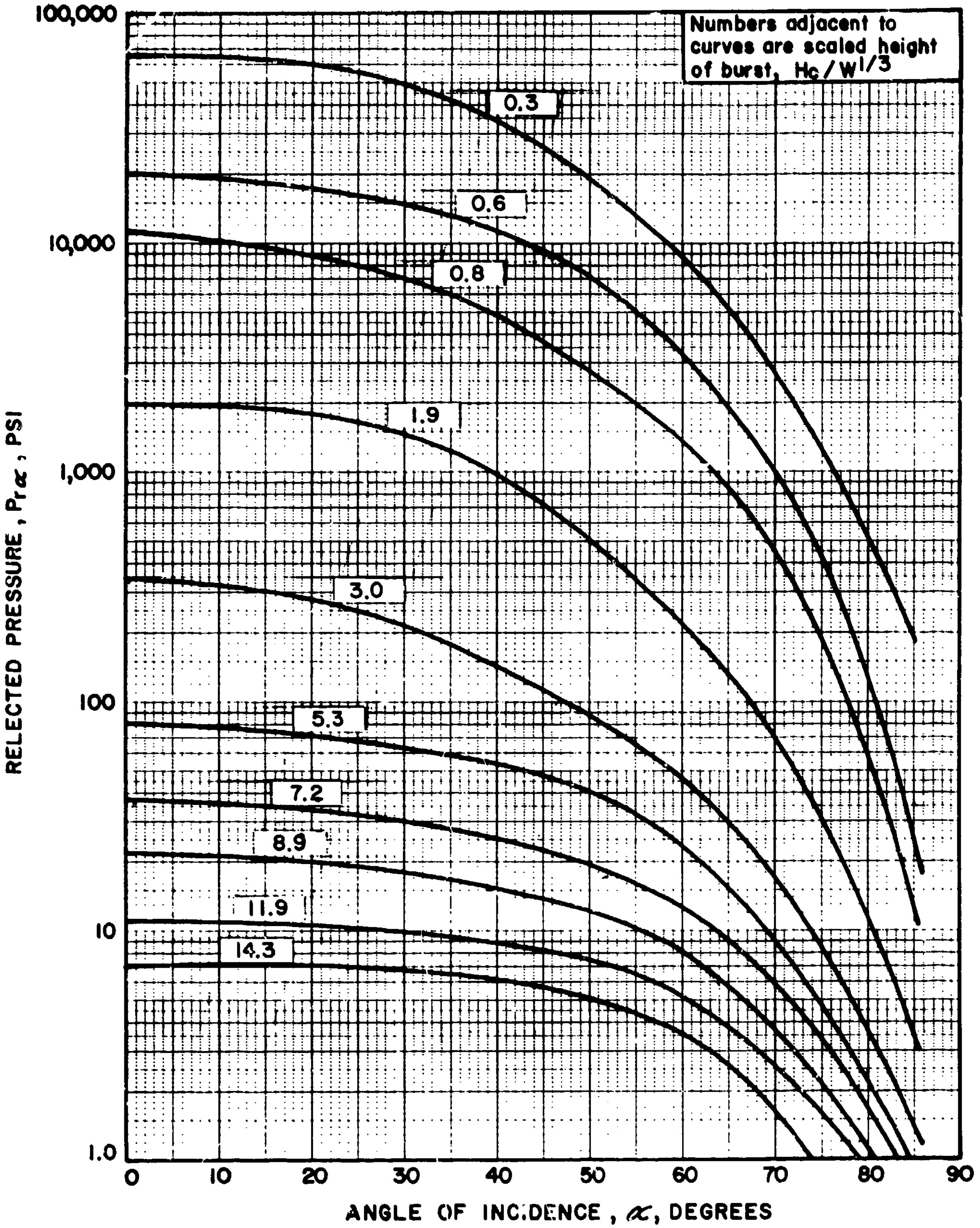


FIGURE 6 BLAST PRESSURES AT GROUND SURFACE DUE TO AN AIR BURST

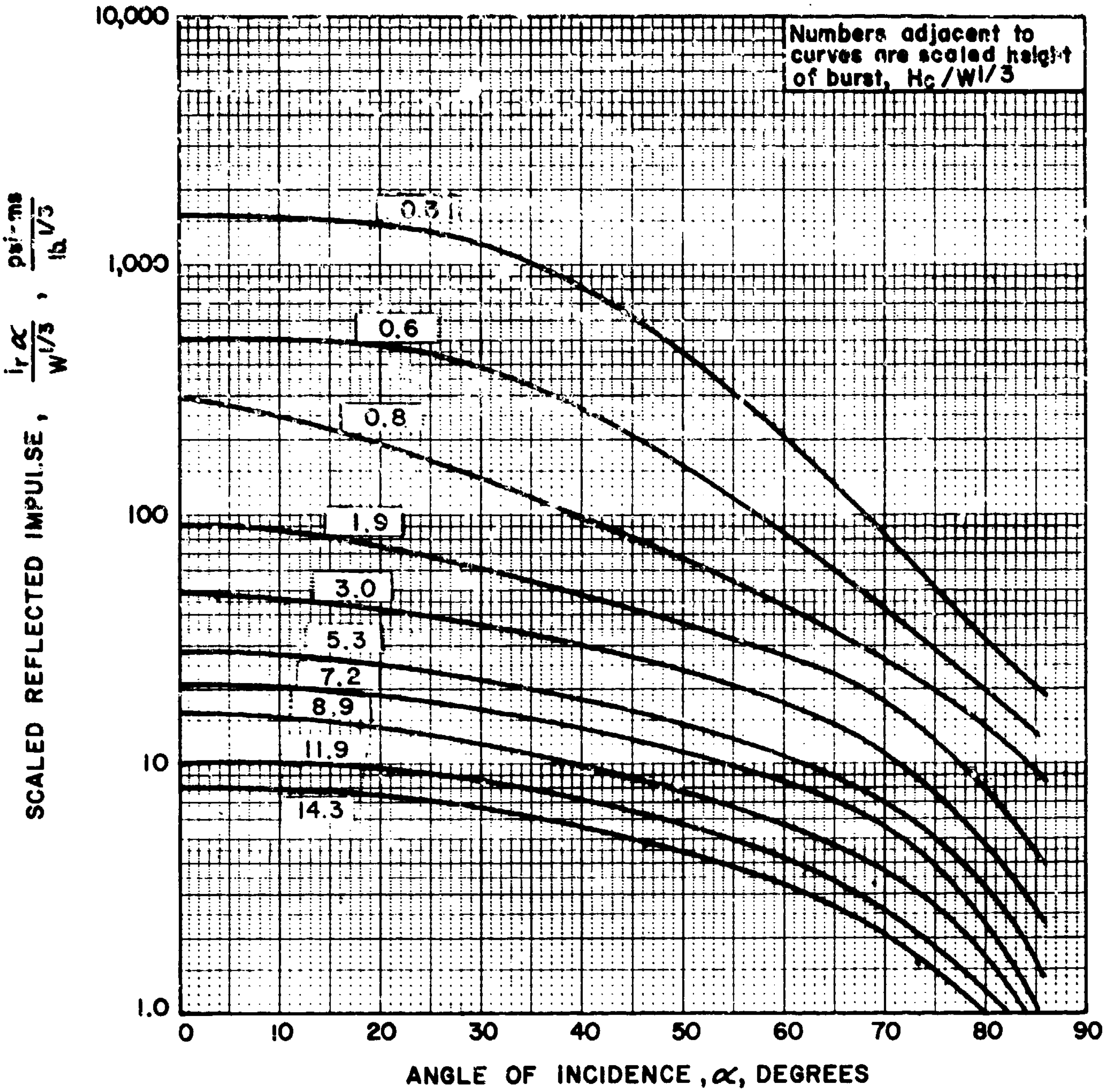
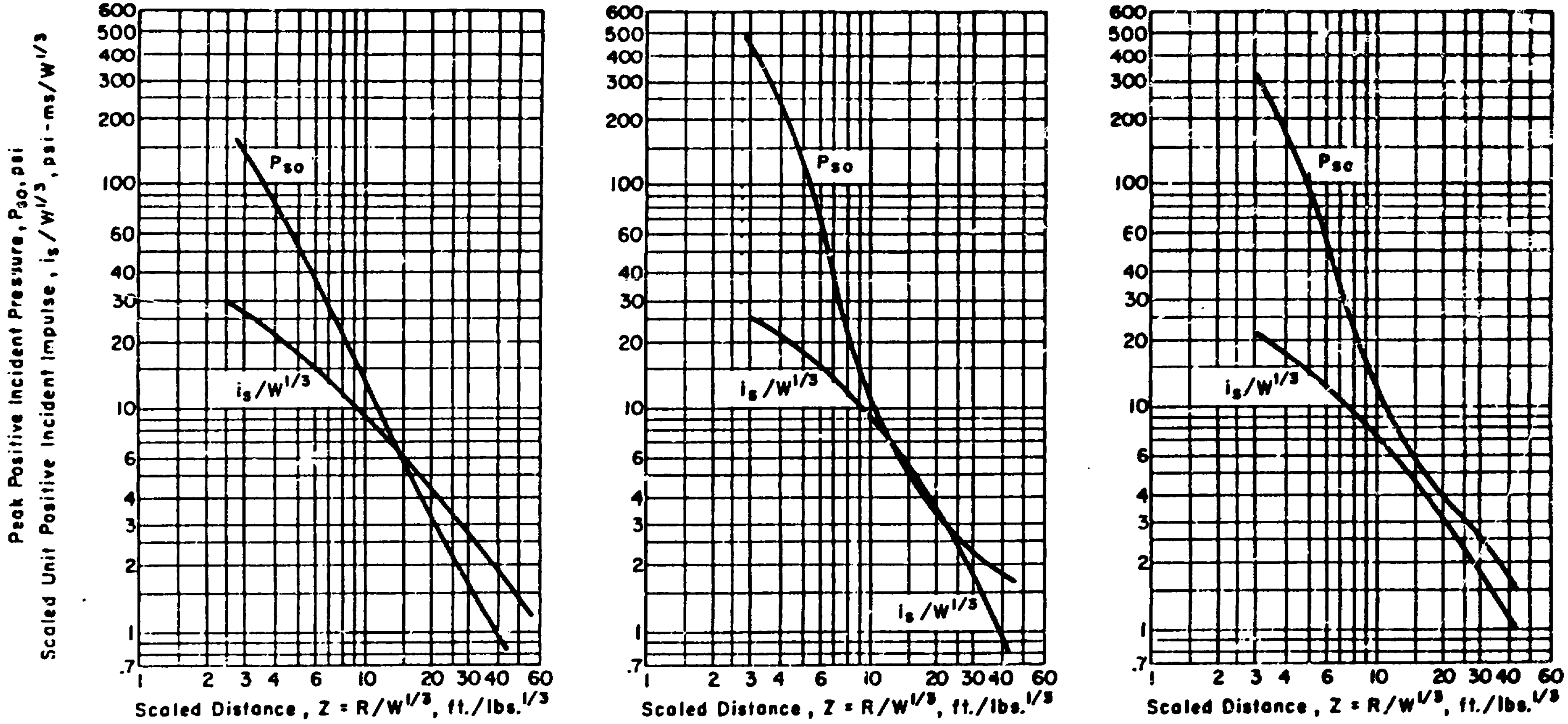


FIGURE 7 SCALED IMPULSE AT GROUND SURFACE DUE TO AN AIR BURST



a. RDX Slurry
Cylindrical

b. RDX 98/2
Orthorhombic

c. RDX 98/2
Cylindrical

FIGURE 8 ILLUSTRATION OF BLAST PARAMETERS FOR OTHER EXPLOSIVE MATERIALS

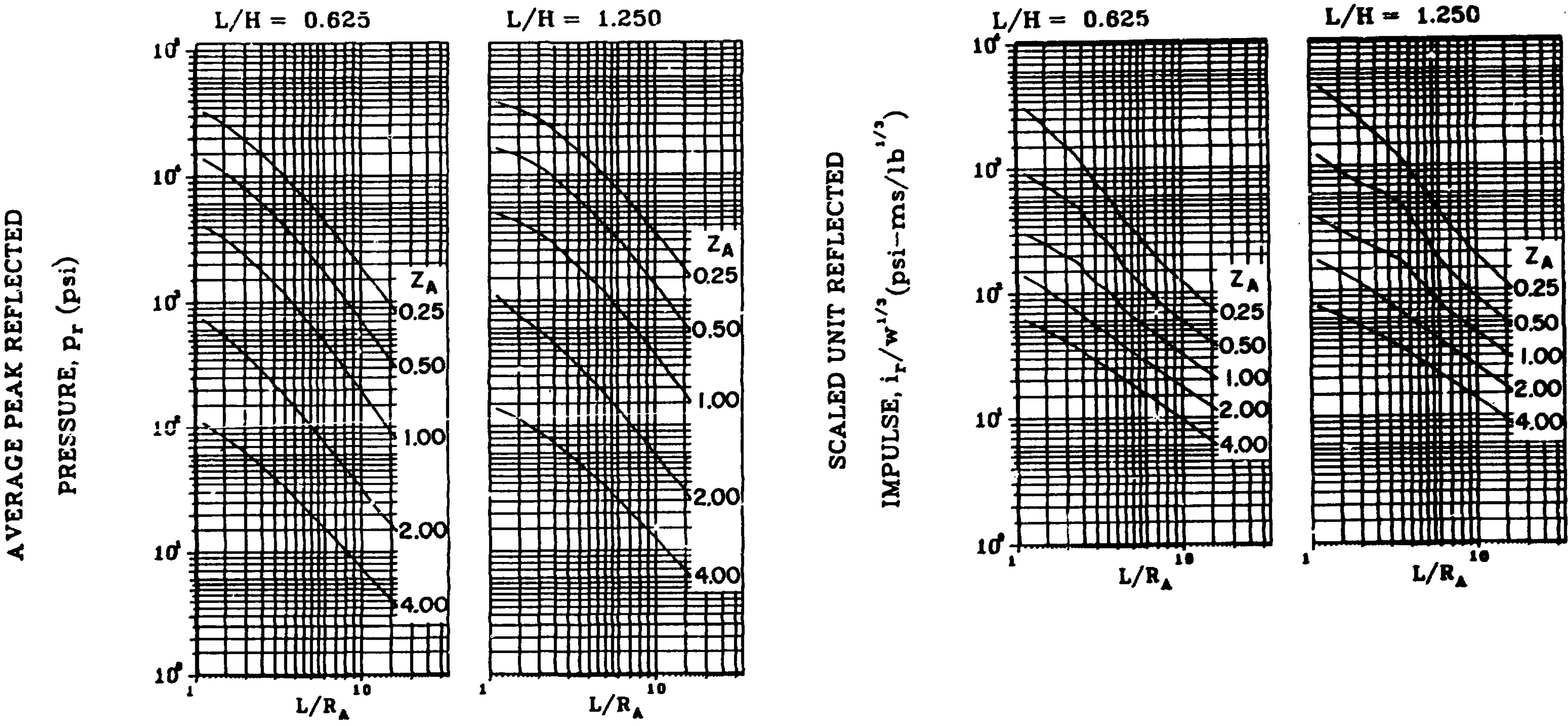


FIGURE 9 ILLUSTRATION OF INTERNAL SHOCK LOADS IN CUBICLE TYPE STRUCTURES

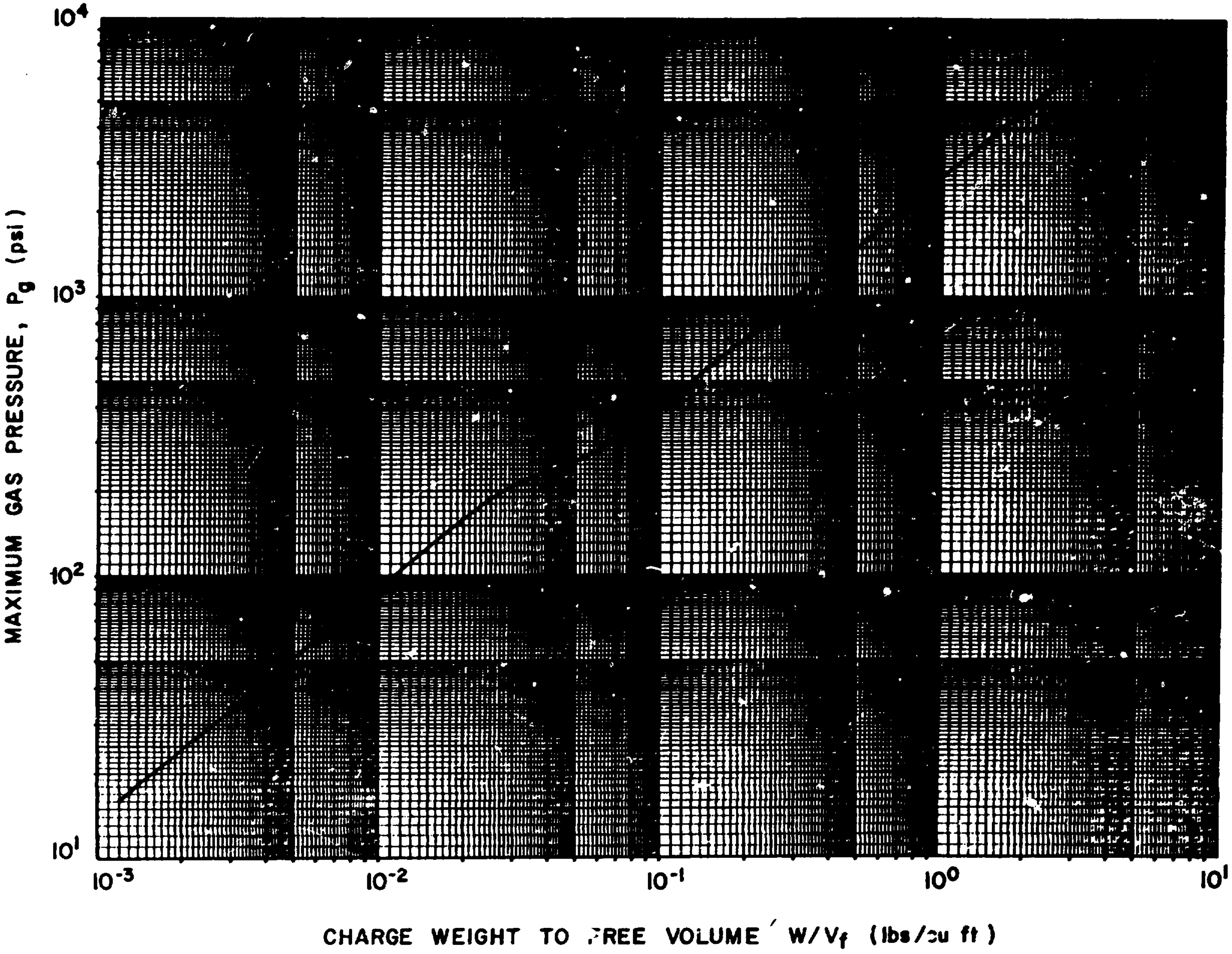


FIGURE 10 PEAK GAS PRESSURE IN A PARTIALLY CONTAINED CHAMBER

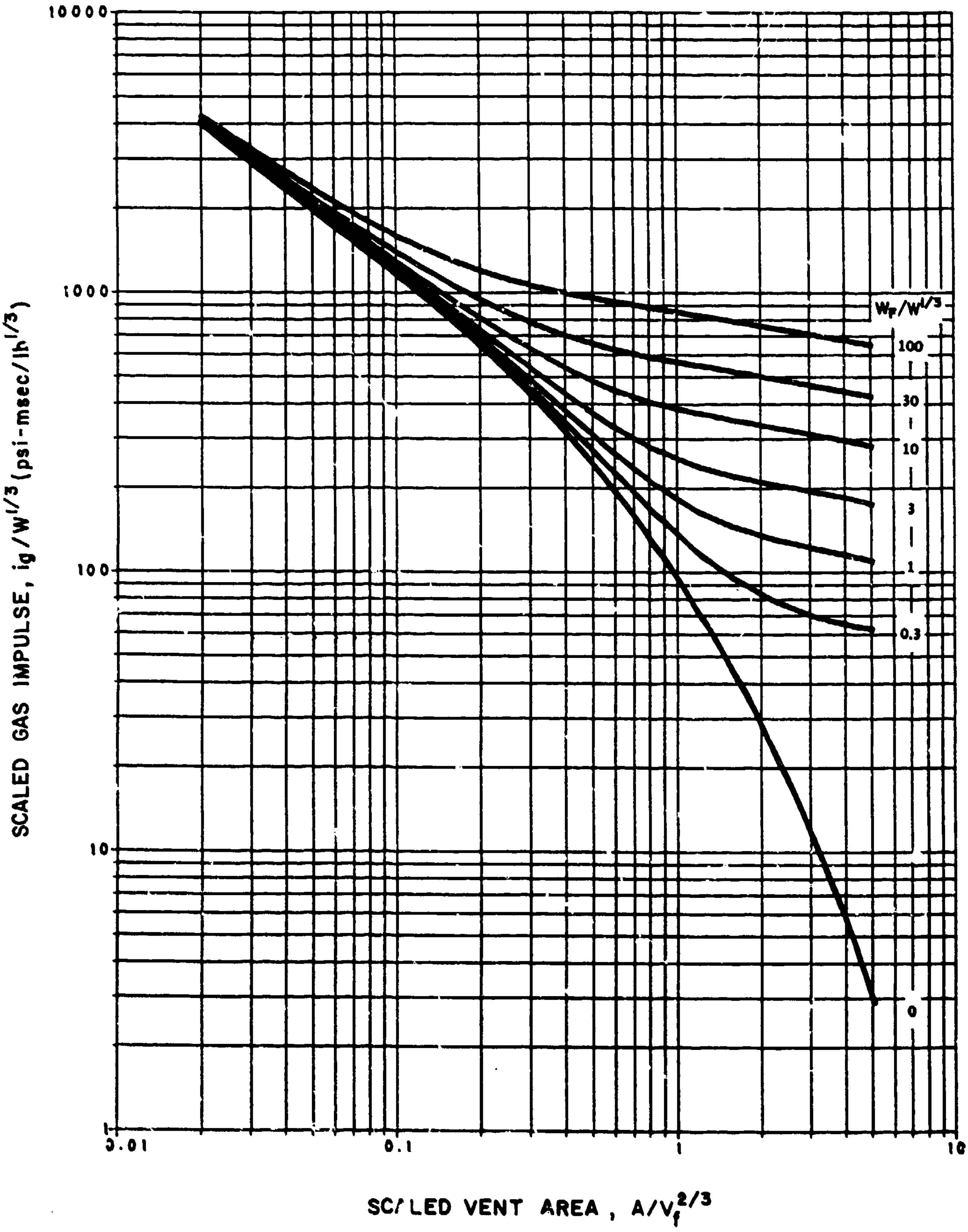


FIGURE 11 SCALED GAS IMPULSE vs. VENT OPENING

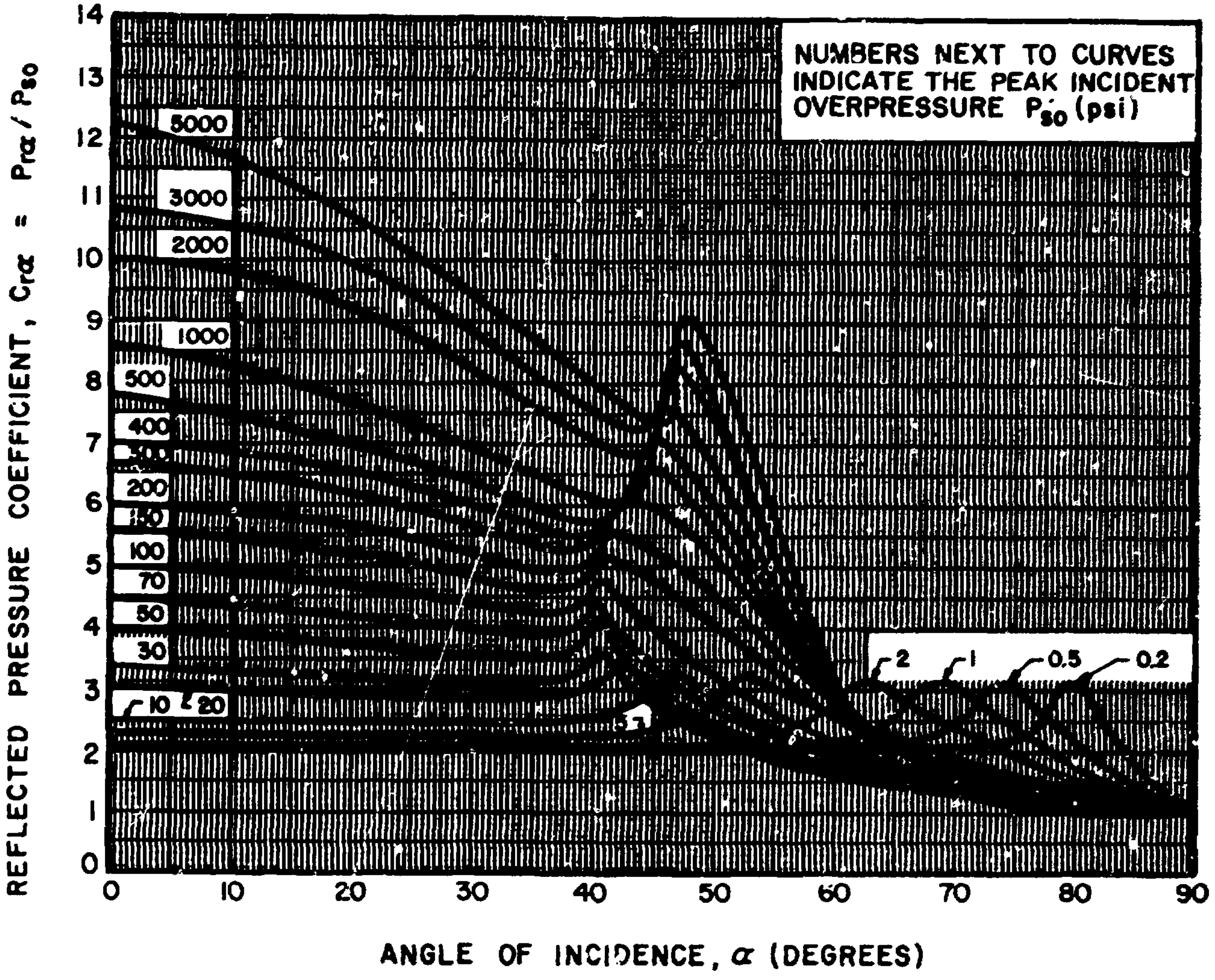


FIGURE 12 REFLECTED PRESSURE COEFFICIENT VERSUS ANGLE OF INCIDENCE

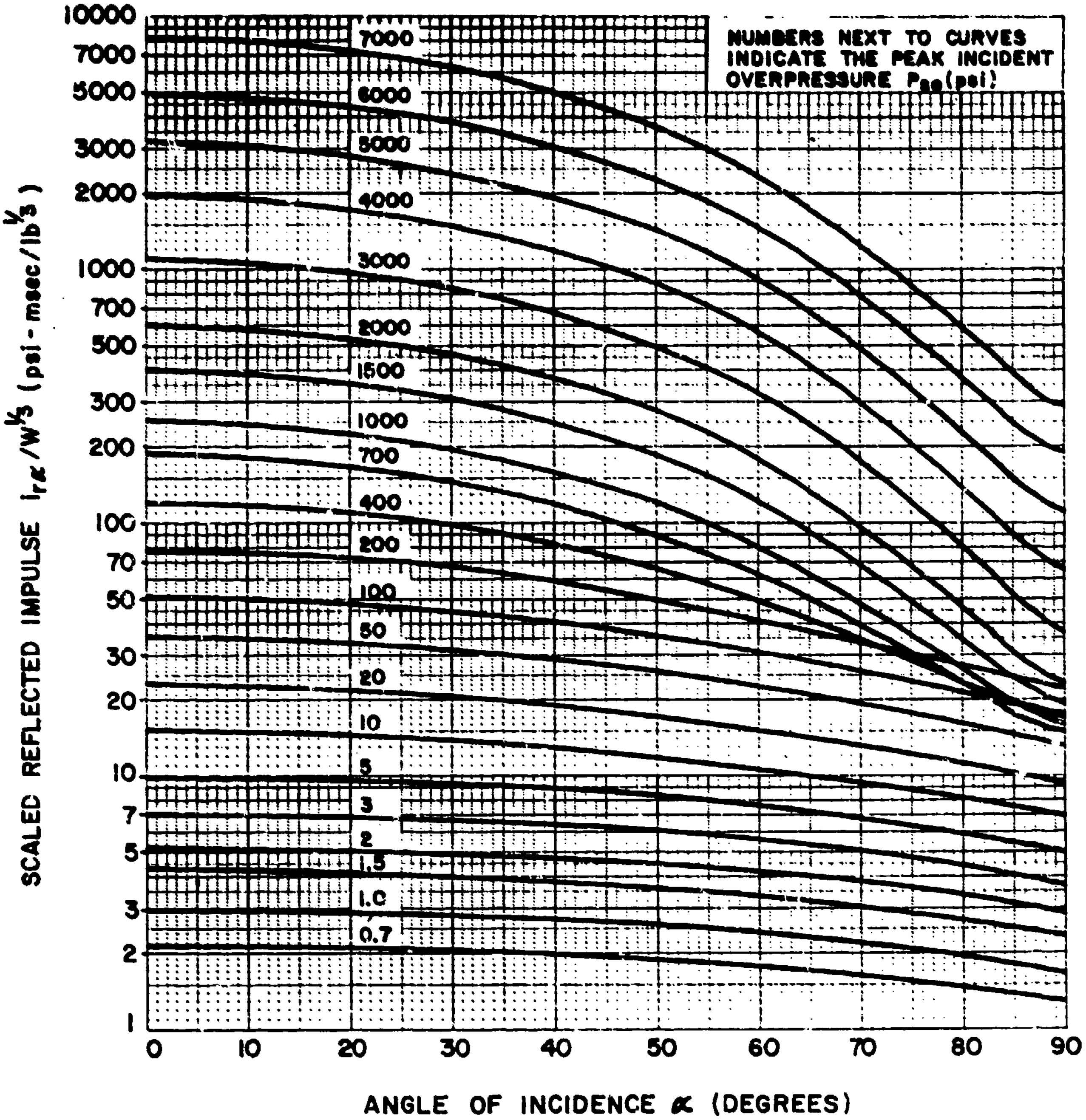
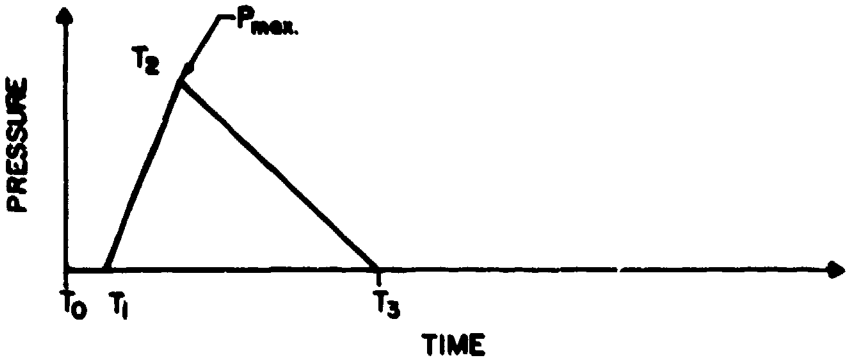
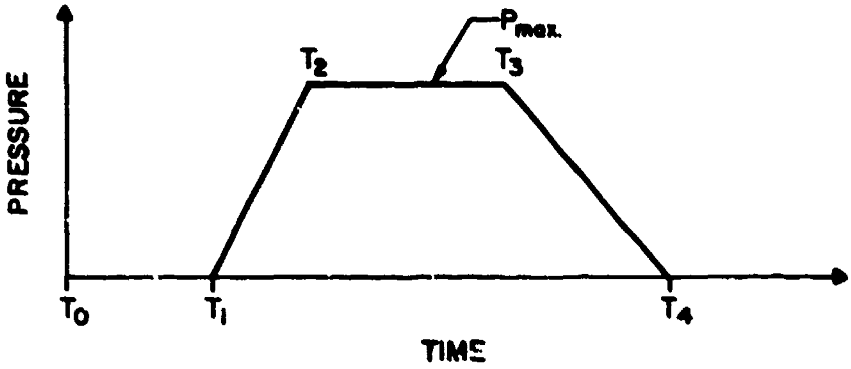


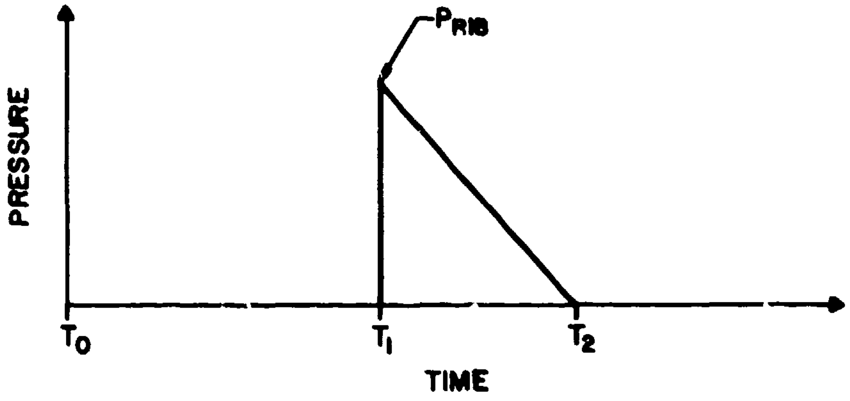
FIGURE 13 REFLECTED SCALED IMPULSE VERSUS ANGLE OF INCIDENCE



a. INTERIOR FRONT WALL SURFACE



b. INTERIOR SIDE WALL OR ROOF SURFACE



c. INTERIOR BACK WALL SURFACE

FIGURE 14 IDEALIZED INTERIOR BLAST LOADS

PRIMARY AND SECONDARY FRAGMENTS

FRAGMENTS	DESIGN PARAMETERS
PRIMARY FRAGMENTS	ESTABLISH FRAGMENT CONFIGURATION
	DETERMINE INITIAL VELOCITY
	DETERMINE VARIATION OF VELOCITY WITH DISTANCE
	DETERMINE IMPACT CHARACTERISTICS
	DETERMINE IMPACT EFFECTS
SECONDARY FRAGMENTS	ESTABLISH FRAGMENT CONFIGURATION
	DETERMINE BLAST LOAD ACTING ON FRAGMENT
	EVALUATE FRAGMENT VELOCITY
	DETERMINE DIRECTION OF FLIGHT
	DETERMINE IMPACT CHARACTERISTICS
	DETERMINE IMPACT EFFECTS

FIGURE 15

SHOCK LOADS

STRUCTURE MOTIONS	DESIGN PROCEDURE
1. AIR BLAST MOTIONS	INTERGRATION PROCEDURE
2. AIR INDUCED GROUND MOTIONS	EMPERICAL PROCEDURE
3. GROUND INDUCED MOTIONS	EMPERICAL PROCEDURE
4. SHOCK RESPONSE SPECTRA	DETERMINE OF INTERNAL MOTIONS AND STRESSES IN EQUIPMENT

FIGURE 16

VOLUME III
PRINCIPLES OF DYNAMIC ANALYSIS

- RESISTANCE-DEFLECTION FUNCTIONS
  1. ULTIMATE RESISTANCE FOR ONE WAY SLABS AND BEAMS
  2. ULTIMATE RESISTANCE AND CRACK LINE PATTERNS FOR TWO-WAY SLABS AND FLAT SLABS
  3. ELASTIC, ELASTO-PLASTIC AND PLASTIC DEFLECTION CRITERIA

- DYNAMICALLY EQUIVALENT SYSTEMS
  1. LOAD, MASS AND RESISTANCE FACTORS
  2. LOAD-MASS FACTORS
  3. NATURAL PERIOD OF VIBRATION

- DYNAMIC ANALYSIS
  1. DESIGN CHART METHOD: 216 CHARTS FOR VARIOUS LOAD TYPES
  2. NUMERICAL INTERGATION PROCEDURES:
     - A. AVERAGE ACCELERATION METHOD
     - B. ACCELERATION IMPULSE EXTRAPOLATION METHOD
     - C. TWO-DEGREE-OF-FREEDOM SYSTEM AND DAMPING
  3. IMPULSE METHOD

FIGURE 17

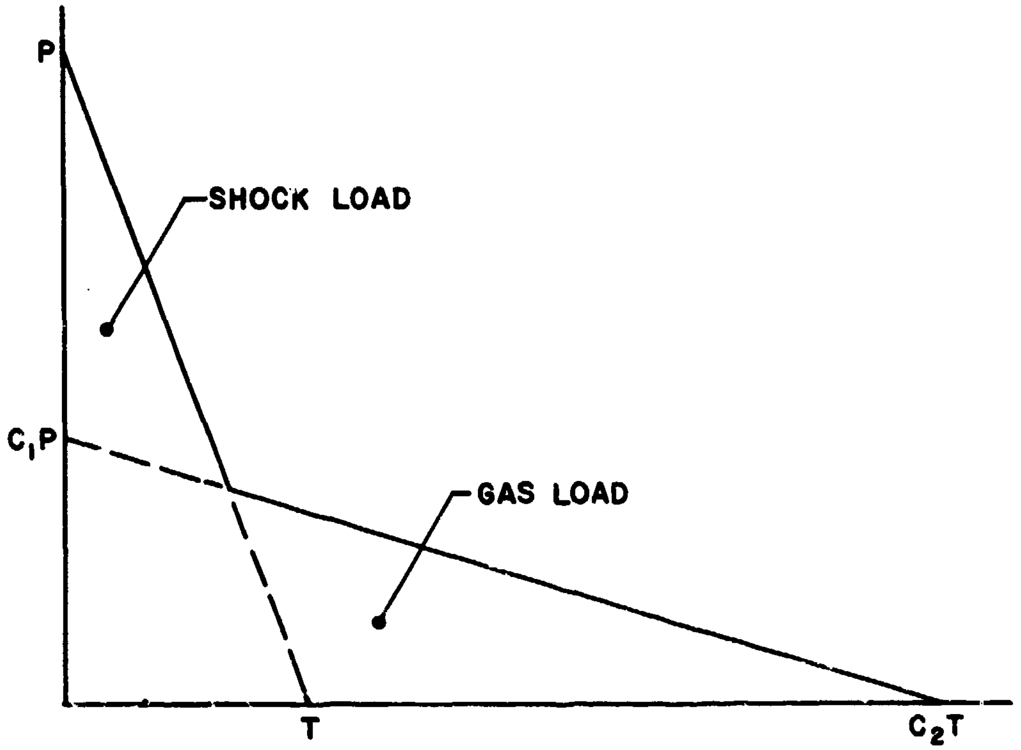


FIGURE 18 IDEALIZED BILINEAR-TRIANGULAR PRESSURE-TIME LOAD

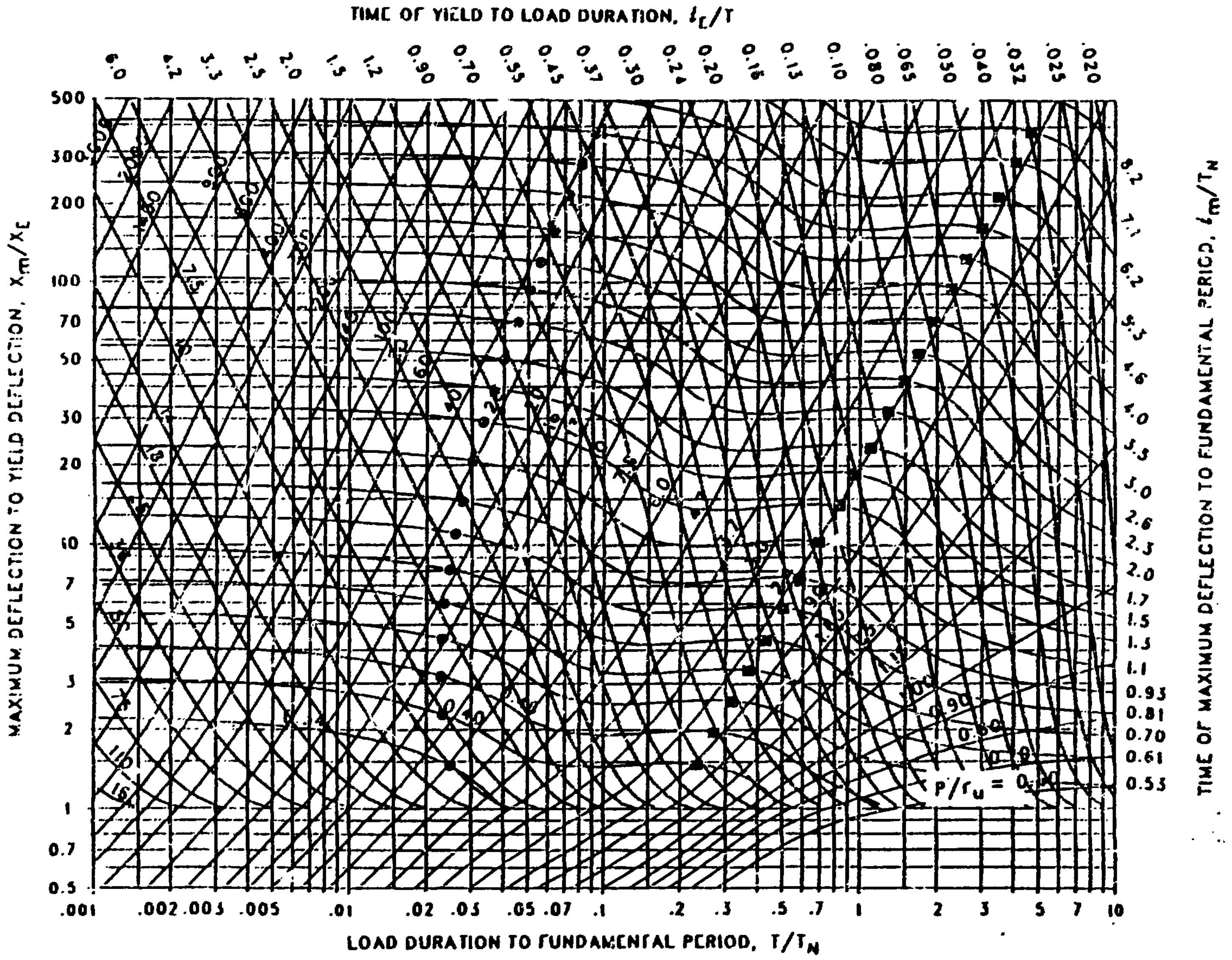


FIGURE 19 MAXIMUM RESPONSE OF ELASTO-PLASTIC SYSTEM FOR BILINEAR-TRIANGULAR PULSE (C_1=0.178, C_2=10)

VOLUME IV
REINFORCED CONCRETE DESIGN

• DYNAMIC CAPACITY OF MATERIALS	1.	INCREASE DYNAMIC INCREASE FACTORS
	2.	INCREASE MINIMUM YIELD STRENGTH
	3.	INCREASE SHEAR CAPACITY
• DESIGN FOR CLOSE-IN EFFECTS	1.	LACED REINFORCED CONCRETE
	2.	SINGLE LEG STIRRUPS
• DESIGN FOR INTERMEDIATE RANGE	1.	ONE AND TWO WAY PANELS
	2.	BEAM AND COLUMNS
	3.	FLAT SLAB CONSTRUCTION
	4.	TENSION MEMBRANE ACTION
• FOUNDATION DESIGN	1.	OVERTURNING ANALYSIS
	2.	SOIL/STRUCTURE INTERACTION
	3.	FOUNDATION COMPONENT DESIGN
• BRITTLE MODE DESIGN	1.	SPALLING
	2.	FRAGMENT PENETRATION
• CONSTRUCTION DETAILING	1.	LACED REINFORCED CONCRETE
	2.	SINGLE LEG STIRRUPS
	3.	BEAM AND COLUMN
	4.	FLAT SLABS
	5.	FOUNDATIONS

FIGURE 20

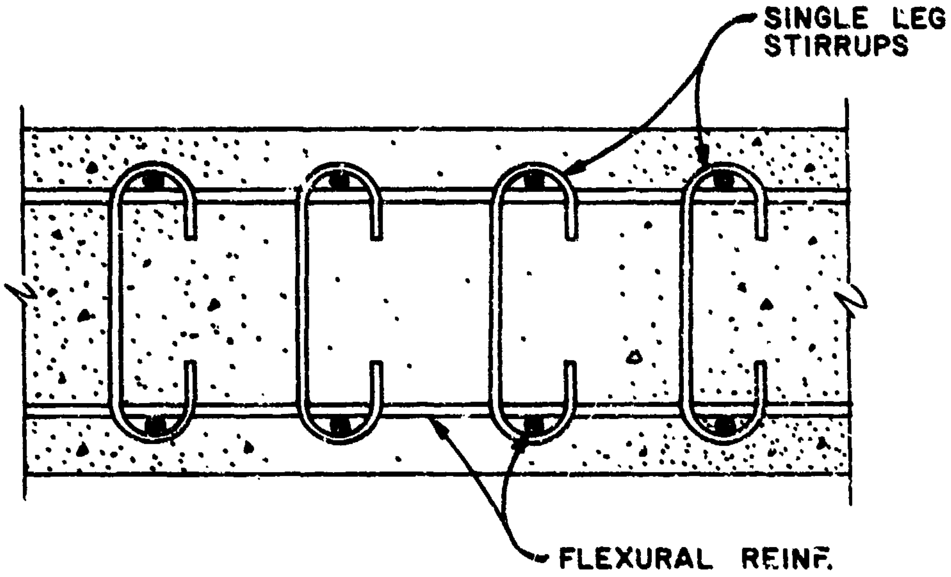


FIGURE 21 SINGLE LEG STIRRUPS

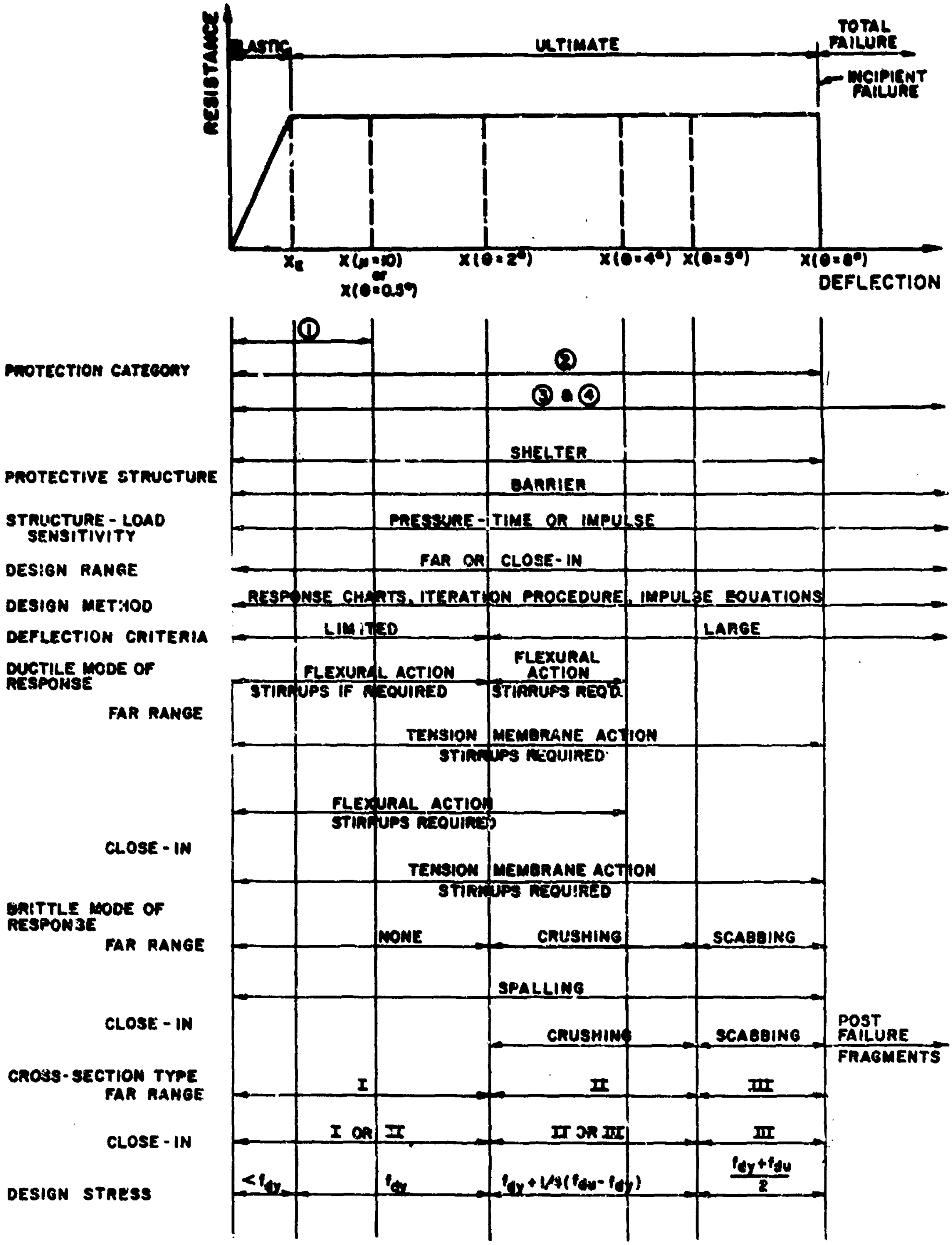


FIGURE 22 RELATIONSHIP BETWEEN DESIGN PARAMETERS FOR UNLACED ELEMENTS

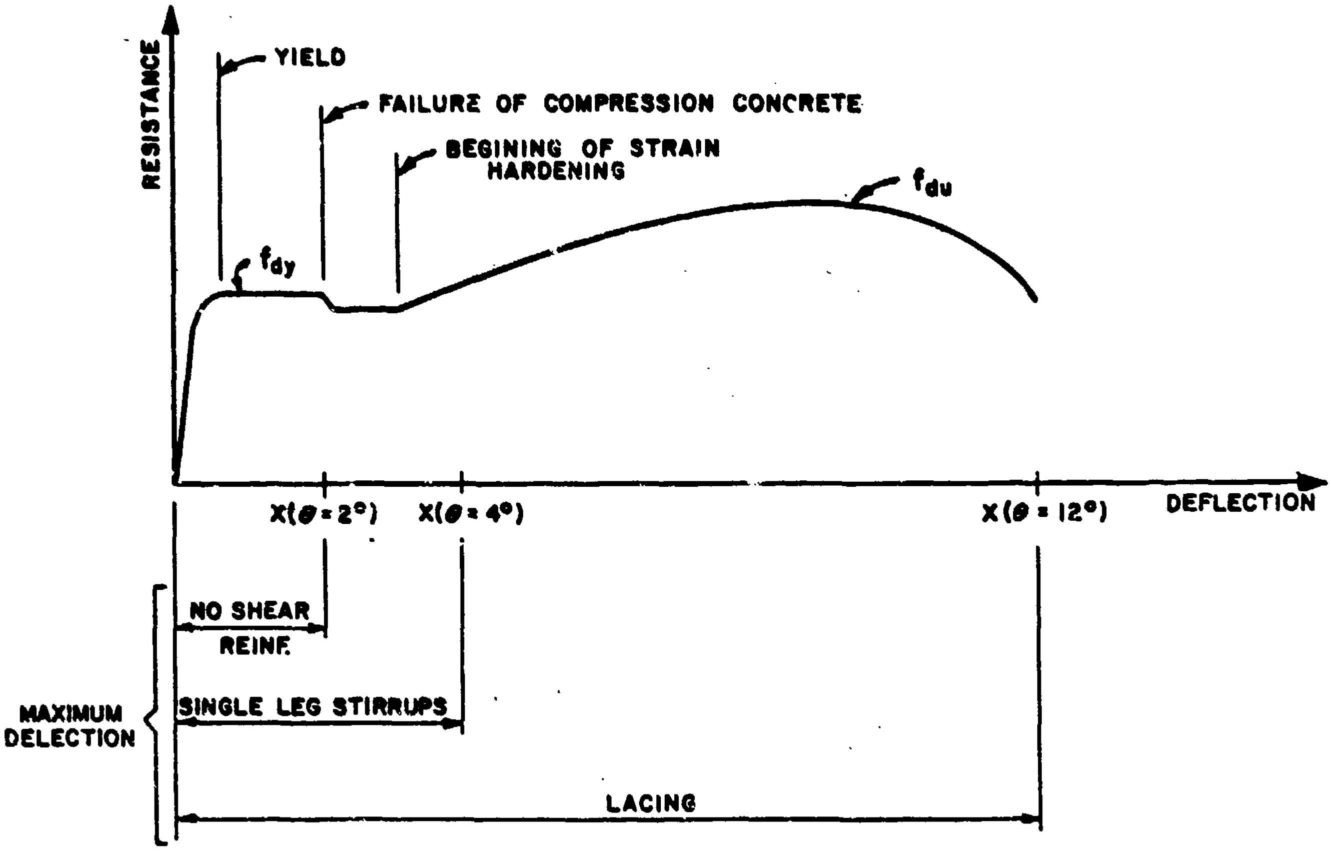


FIGURE 23 TYPICAL RESISTANCE-DEFLECTION CURVE FOR FLEXURAL RESPONSE OF CONCRETE ELEMENTS

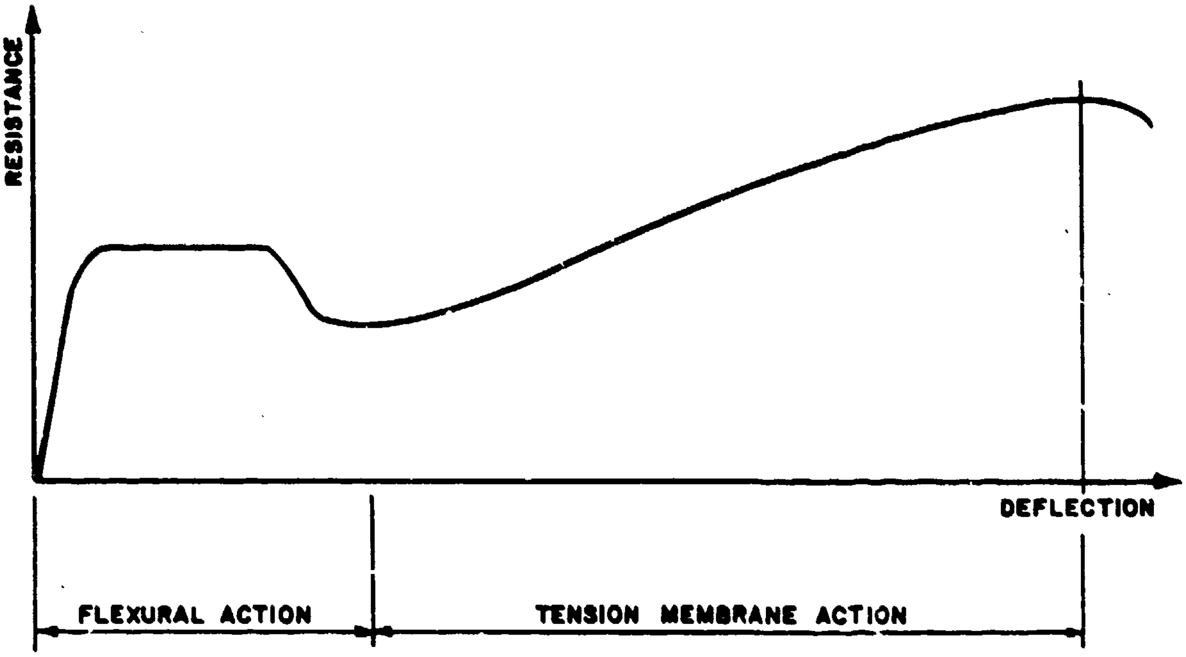


FIGURE 24 TYPICAL RESISTANCE-DEFLECTION CURVE FOR TENSION MEMBRANE RESPONSE OF CONCRETE ELEMENTS

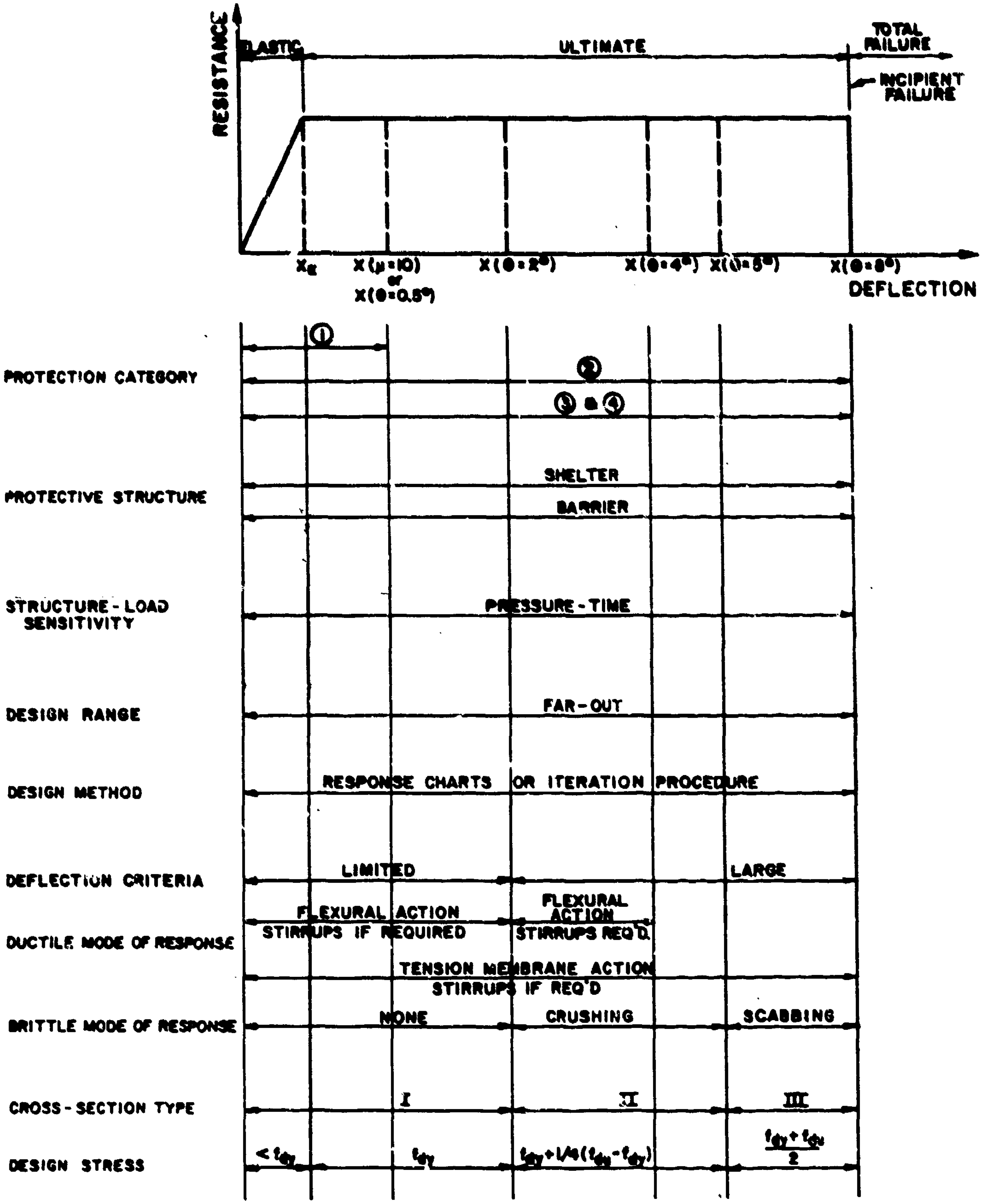


FIGURE 25 RELATIONSHIP BETWEEN DESIGN PARAMETERS FOR FLAT SLABS

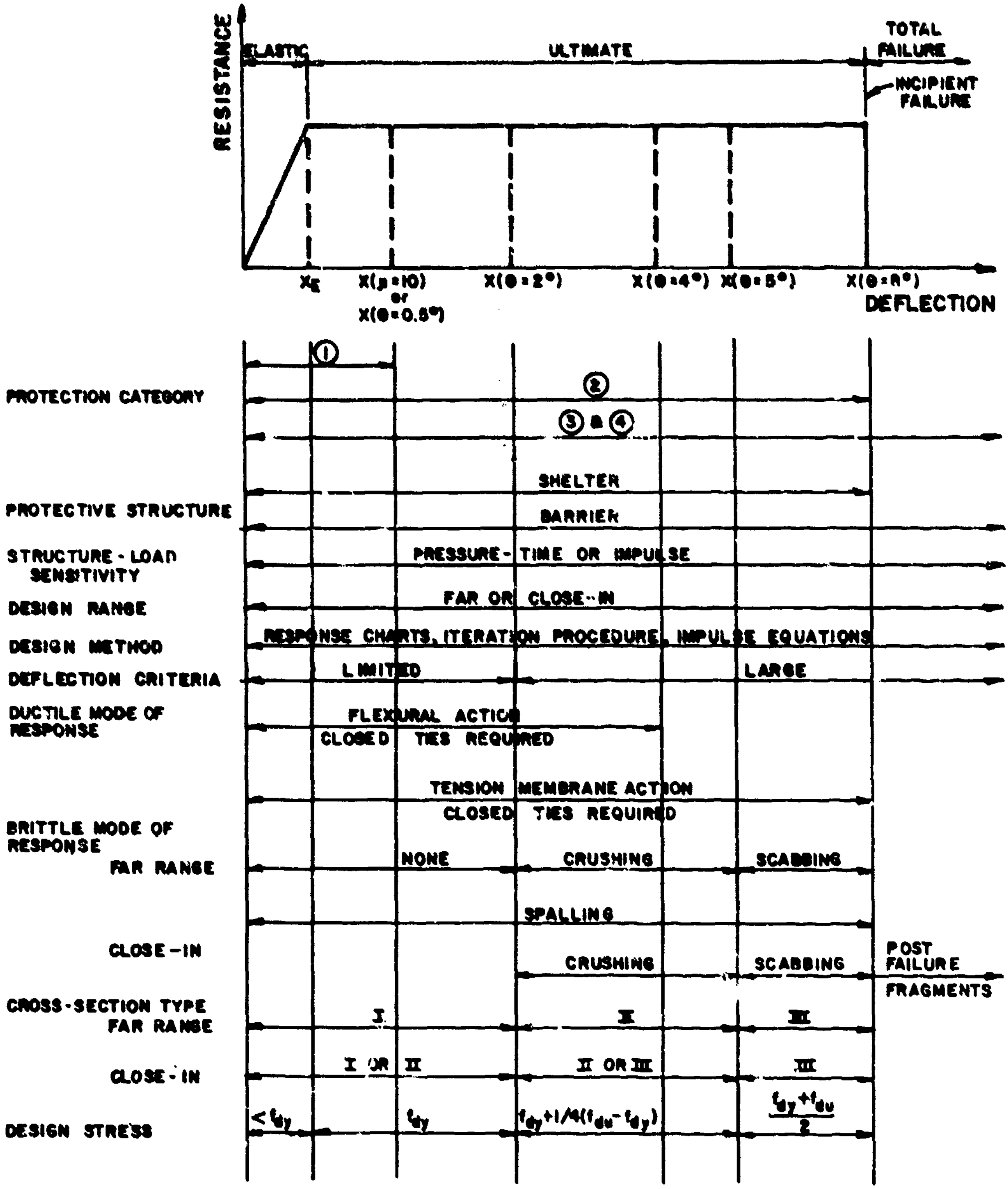


FIGURE 26 RELATIONSHIP BETWEEN DESIGN PARAMETERS FOR BEAMS

VOLUME V
STRUCTURAL STEEL DESIGN

- MECHANICAL PROPERTIES
  1. STATIC STRESSES
  2. DYNAMIC STRESSES
- DESIGN OF ELEMENTS
  1. BEAMS AND PLATES
  2. COLUMNS AND BEAM COLUMNS
  3. BLAST DOORS
  4. COLD FORMED STEEL PANELS
- PREL. FRAME ANALYSIS
  1. SINGLE BAYS AND MULTI BAYS
  2. RIGID FRAMES AND BRACED FRAMES
  3. PRELIMINARY SIZING OF FRAME MEMBERS
- CONSTRUCTION
  1. FRAMING REQUIREMENTS
  2. CONNECTION DETAILS
- FRACTURE DESIGN
  1. CLOSE-IN EFFECTS
  2. STEEL CONTAINMENT STRUCTURES

FIGURE 27

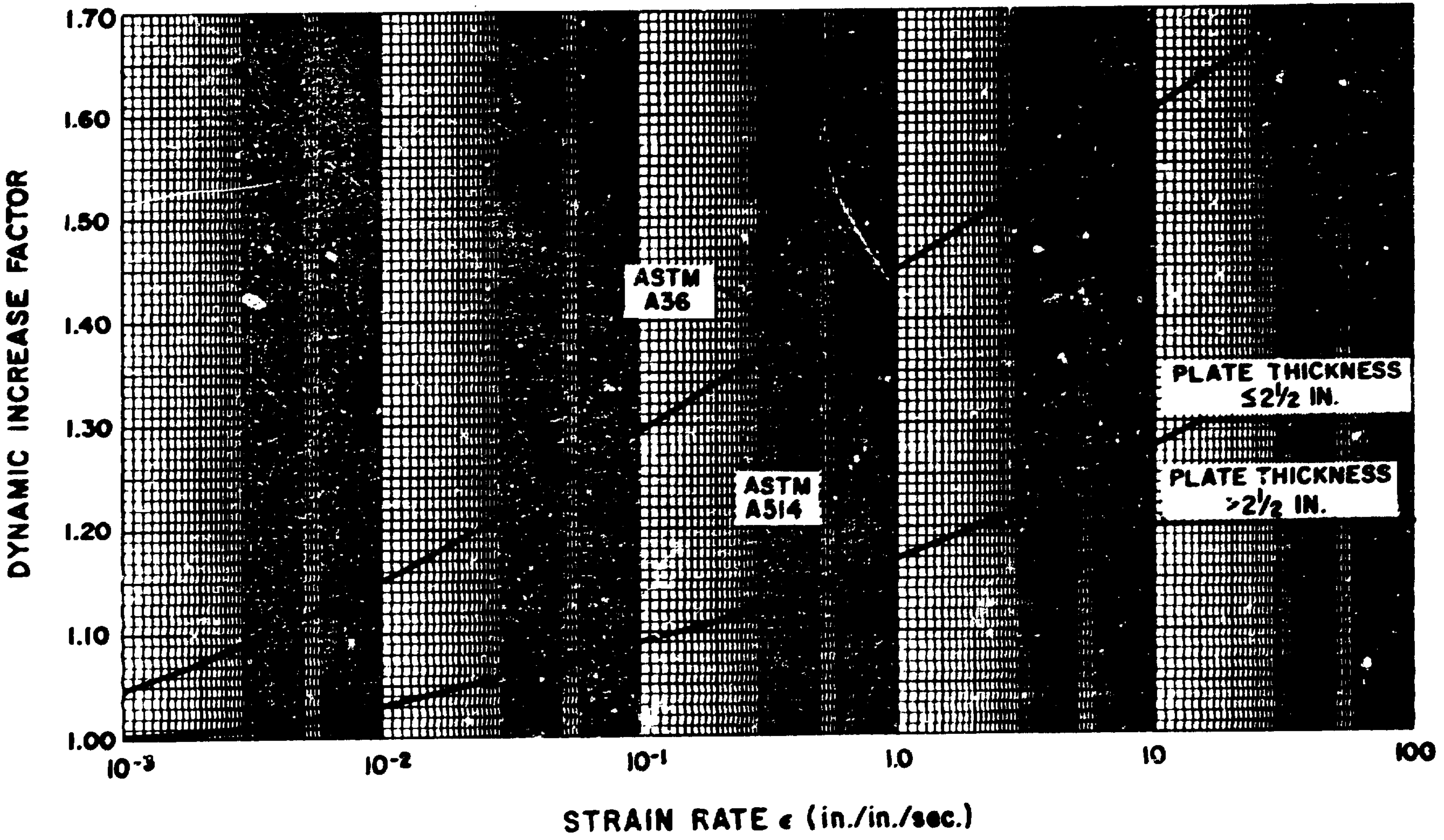
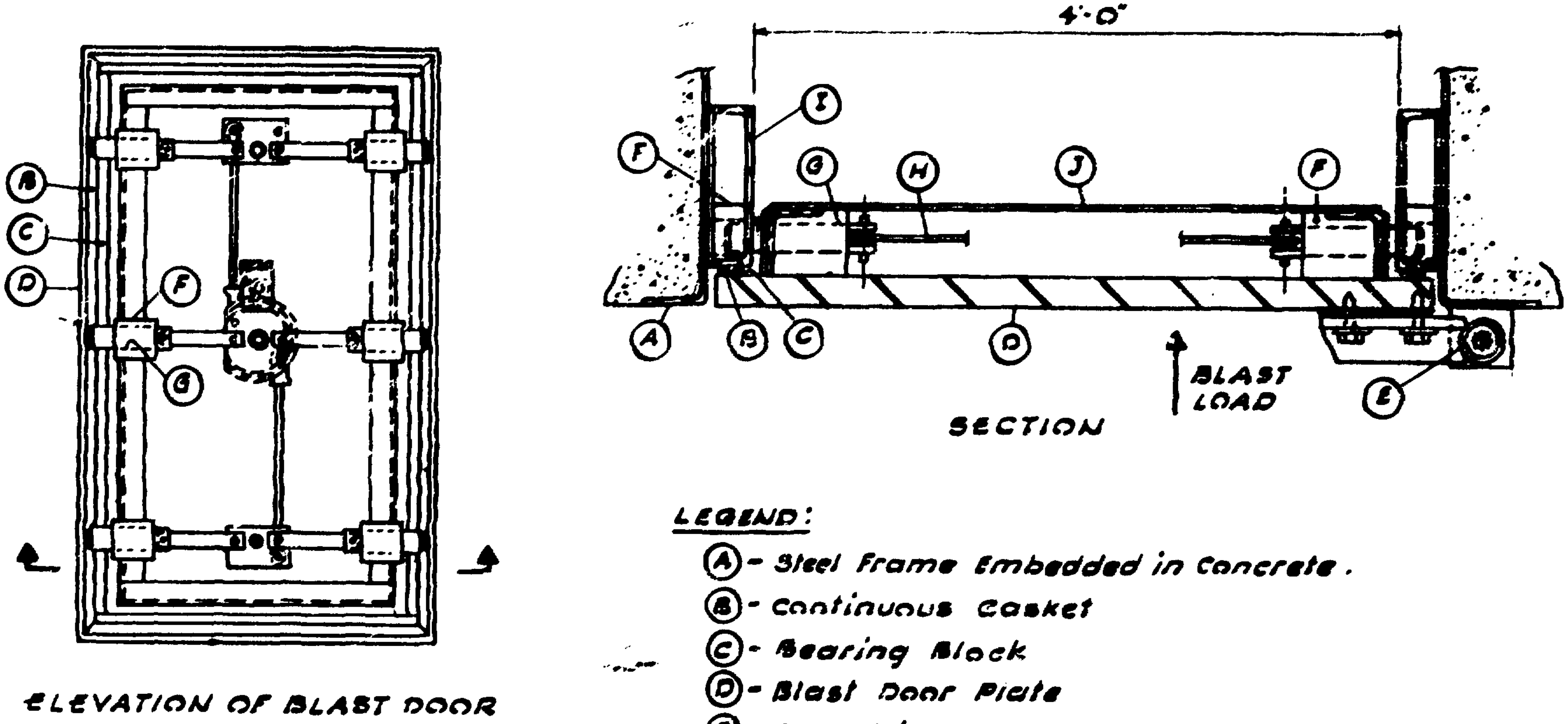


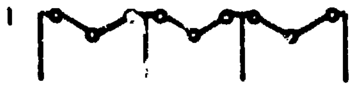
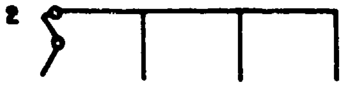
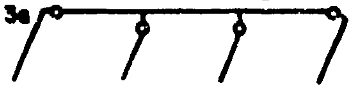
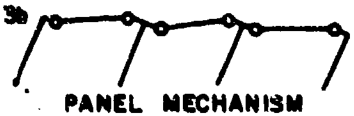
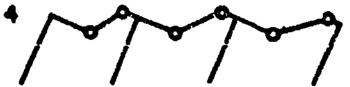
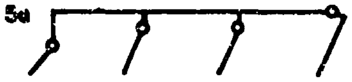
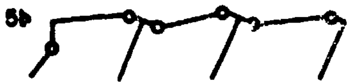
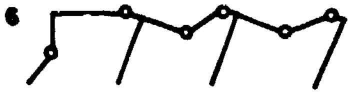
FIGURE 28 DYNAMIC INCREASE FACTORS FOR YIELD STRESSES FOR VARIOUS STRAIN RATES

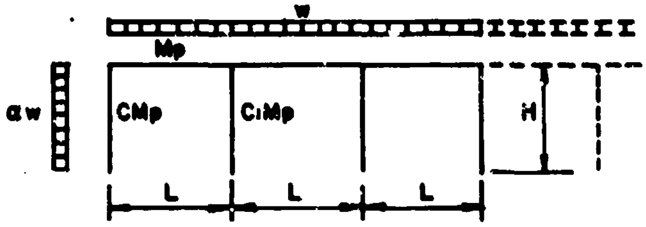


LEGEND:

- Ⓐ - Steel Frame Embedded in Concrete.
- Ⓑ - Continuous Casket
- Ⓒ - Bearing Block
- Ⓓ - Blast Door Plate
- Ⓔ - Door Hinge
- Ⓕ - Reversal Bolt Housing
- Ⓖ - Reversal Bolt
- Ⓗ - Bar Connected to Closure Mechanism
- Ⓘ - Steel Frame Equipped with Blast Door
- Ⓙ - Light Gage Cover Plate

FIGURE 29 STEEL PLATE BLAST DOOR

Collapse Mechanism	Plastic Moment M_p	
	Pinned Bases	Fixed Bases
1  BEAM MECHANISM	$\frac{wL^2}{16}$	$\frac{wL^2}{16}$
2  BEAM MECHANISM	$\frac{\alpha wH^2}{4(2C+1)}$	$\frac{\alpha wH^2}{4(3C+1)}$
3a  PANEL MECHANISM	$\frac{\alpha wH^2}{2} \cdot \frac{1}{2+(n-1)C_1}$ $(C_1 \leq 2)^*$	$\frac{\alpha wH^2}{4} \cdot \frac{1}{1+(n-1)C_1+C}$ $(C_1 \leq 2)^*$
3b  PANEL MECHANISM	$\frac{\alpha wH^2}{4n}$ $(C_1 \geq 2)^*$	$\frac{\alpha wH^2}{2} \cdot \frac{1}{2(n+C)+(n-1)C_1}$ $(C_1 \geq 2)^*$
4  COMBINED MECHANISM	$\frac{w}{8n}(\alpha H^2+\frac{n}{2}L^2)$	$\frac{w}{2} \cdot \frac{\alpha H^2+\frac{n}{2}L^2}{2(2n+C)+(n-1)C_1}$
5a  COMBINED MECHANISM	$\frac{\frac{3}{8}\alpha wH^2}{C+\frac{1}{2}+\frac{C_1}{2}(n-1)}$ $(C_1 \leq 2)^*$	$\frac{\frac{3}{8}\alpha wH^2}{\frac{5}{2}C+(n-1)C_1+\frac{1}{2}}$ $(C_1 \leq 2)^*$
5b  COMBINED MECHANISM	$\frac{\frac{3}{8}\alpha wH^2}{C+(n-\frac{1}{2})}$ $(C_1 \geq 2)^*$	$\frac{\frac{3}{8}\alpha wH^2}{\frac{5}{2}C+(n-1)\frac{C_1}{2}+(n-\frac{1}{2})}$ $(C_1 \geq 2)^*$
6  COMBINED MECHANISM	$\frac{\frac{w}{8}\left[3\alpha H^2+(n-1)L^2\right]}{C+(2n-\frac{3}{2})}$	$\frac{\frac{w}{8}\left[3\alpha H^2+(n-1)L^2\right]}{\frac{5}{2}C+(n-1)\frac{C_1}{2}+(2n-\frac{3}{2})}$



n = Number of bays = 1,2,3...

w = Uniform equivalent static load

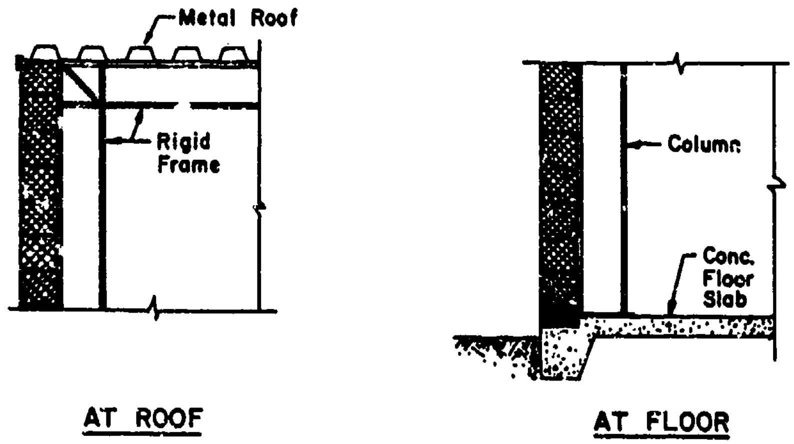
* For $C_1 = 2$ hinges form in the girders and columns at interior joints.

FIGURE 30 COLLAPSE MECHANISMS FOR RIGID FRAMES

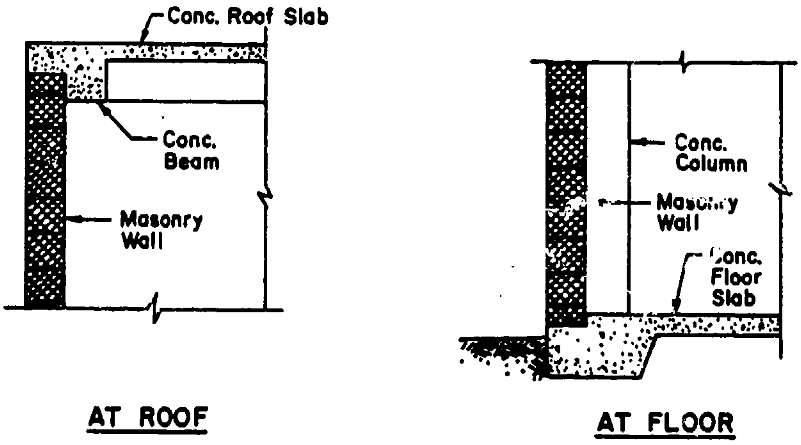
VOLUME VI
SPECIAL CONSIDERATIONS IN EXPLOSIVE FACILITY DESIGN

• MASONRY DESIGN	1.	DESIGN PROCEDURES AND CONSTRUCTION METHOD
• PRECAST CONCRETE DESIGN	1.	DESIGN PROCEDURES AND CONSTRUCTION METHOD
• SPECIAL PROVISIONS FOR PRE-ENGINEERED BUILDINGS	1. 2.	DESIGN LOADS AND REQUIREMENTS TYPICAL SPECIFICATIONS
• SUPPRESSIVE SHIELDING	1.	OUTLINE OF DATA CONTAINED IN "SUPPRESSIVE SHIELDS - STRUCTURAL DESIGN AND ANALYSIS HANDBOOK" (HNDM 1110-1-2)
• BLAST RESISTANT WINDOWS	1.	DESIGN PROCEDURES FOR GLAZING AND WINDOW FRAMES SUBJECTED TO BLAST LOADS
• DESIGN LOADS FOR UNDERGROUND STRUCTURES	1.	OUTLINE OF DATA CONTAINED IN "FUNDAMENTALS OF PROTECTIVE DESIGN FOR CONVENTIONAL WEAPONS"
• EARTH-COVERED ARCH-TYPE MAGAZINES	1.	INVESTIGATION, DESIGN, CONSTRUCTION AND STANDARD DRAWINGS FOR MAGAZINES
• SHOCK ISOLATION SYSTEM	1.	METHOD AND PROCEDURES FOR DESIGN OF SHOCK ISOLATION SYSTEMS ARE PRESENTED FOR BOTH PERSONNEL AND EQUIPMENT
• BLAST VALVES	1.	DISCUSS VARIOUS TYPE OF BLAST VALVES AND ASSOCIATED EQUIPMENT

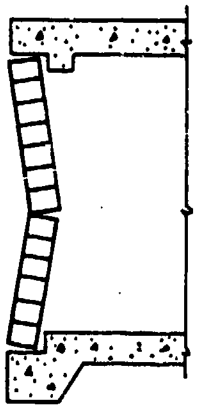
FIGURE 31



a) MASONRY WITH FLEXIBLE SUPPORT

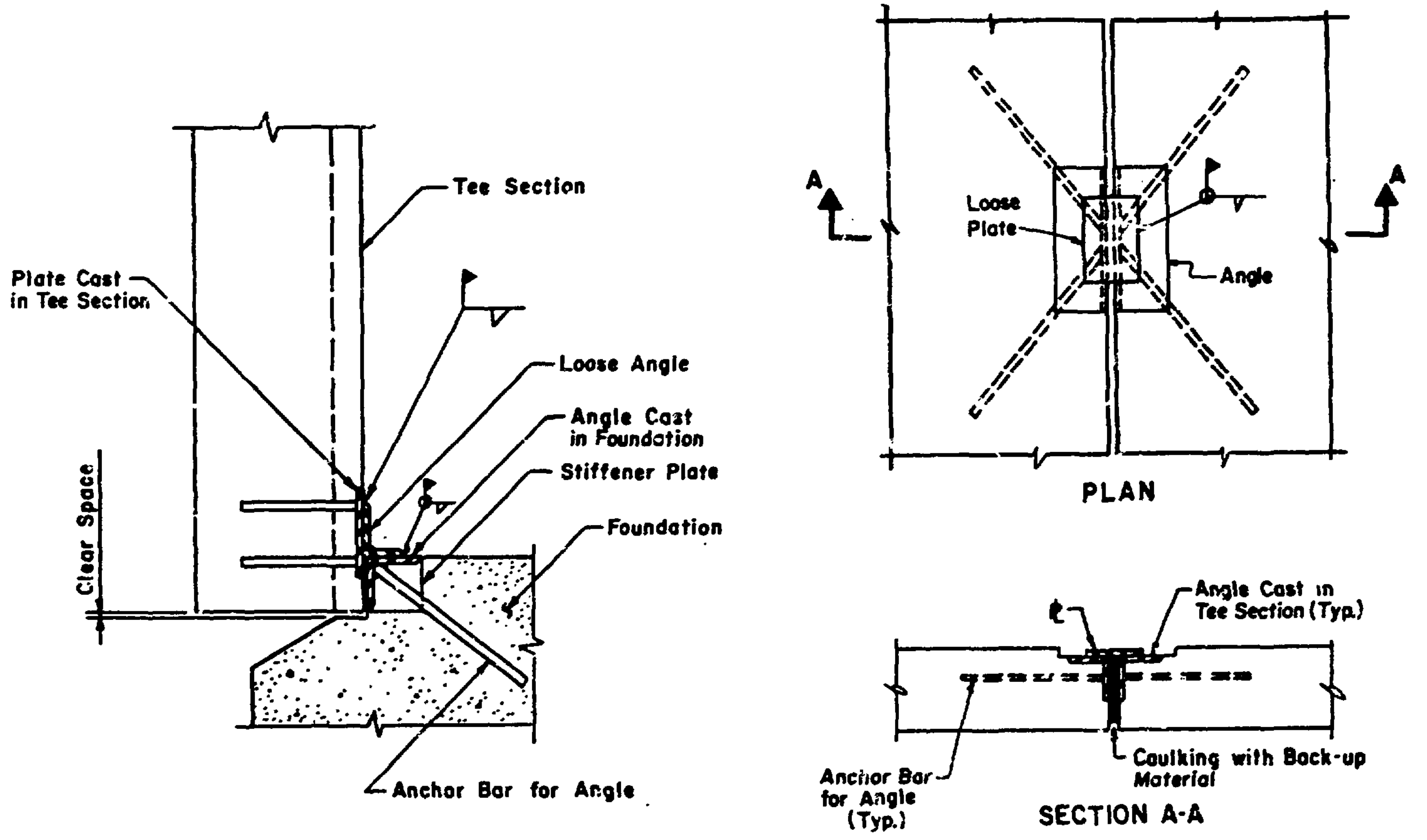


b) MASONRY WITH RIGID SUPPORT



c) ARCHING ACTION OF NON-REINFORCED MASONRY WALL

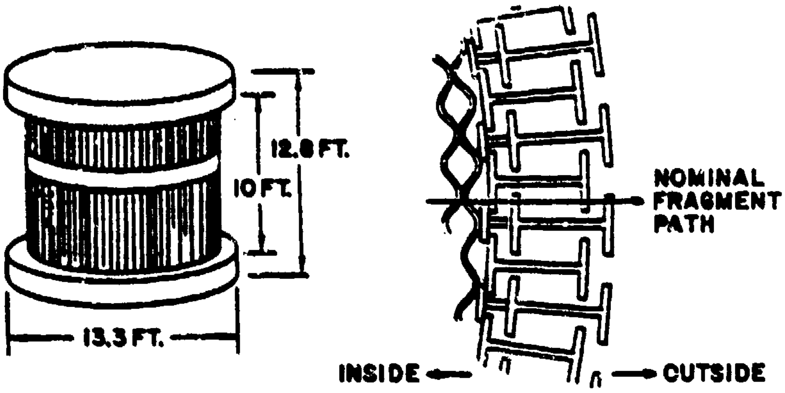
FIGURE 32 MASONRY WALL CONSTRUCTION



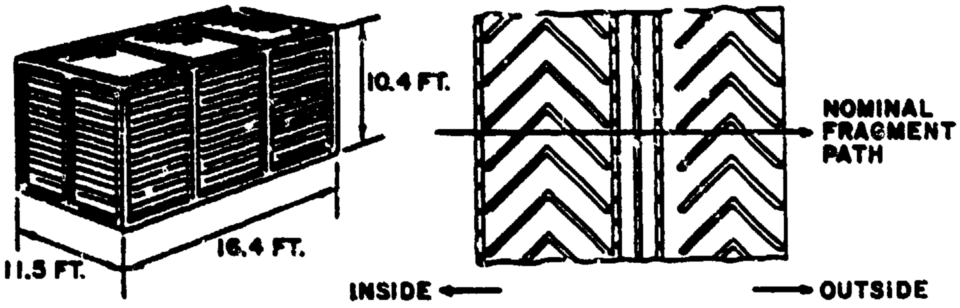
a) WALL PANEL-TO-FOUNDATION CONNECTION

b) TYPICAL PANEL SPLICE

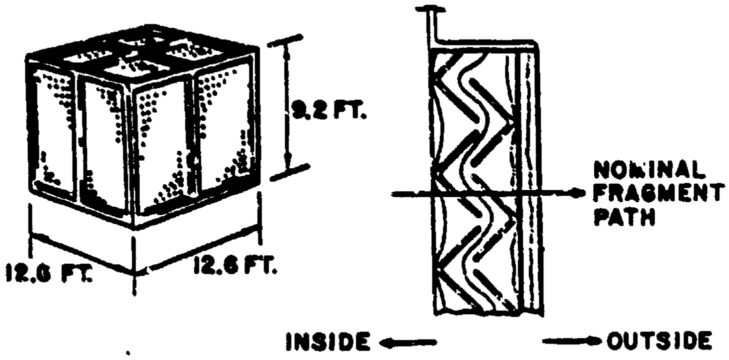
FIGURE 33 TYPICAL PRECAST PANEL CONNECTIONS



SUPPRESSIVE SHIELD GROUP 3
(GROUPS 1 & 2 ARE SIMILAR, BUT MUCH LARGER, AND HAVE THREE EXTERNAL RINGS)



SUPPRESSIVE SHIELD GROUP 4



SUPPRESSIVE SHIELD GROUP 5

FIGURE 34 EXAMPLES OF SUPRESSIVE SHIELDS

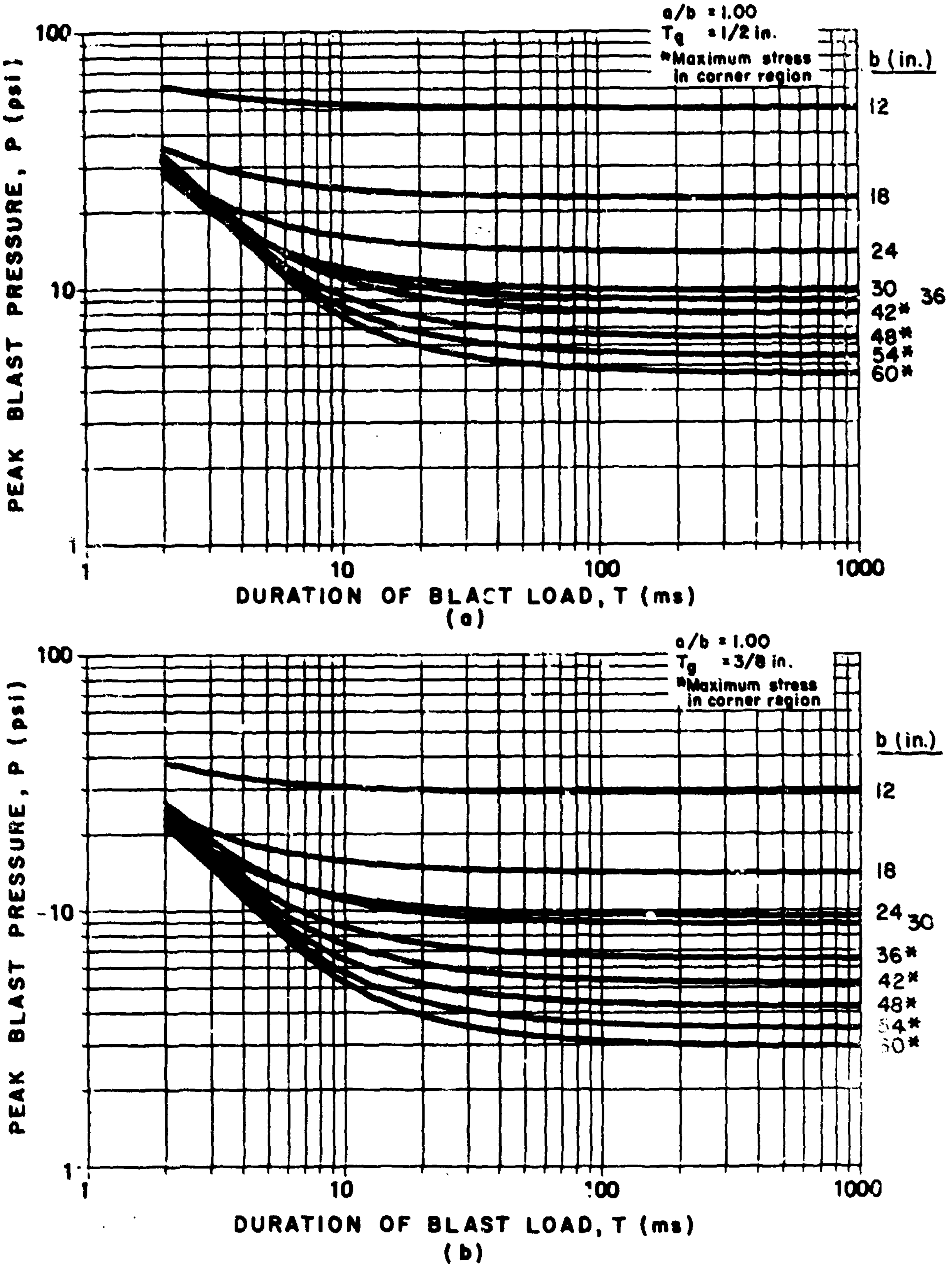


FIGURE 35 PEAK BLAST PRESSURE CAPACITY FOR TEMPERED GLASS PANES: L/H = 1.00, Tg = 1/2 AND 3/8 INS.

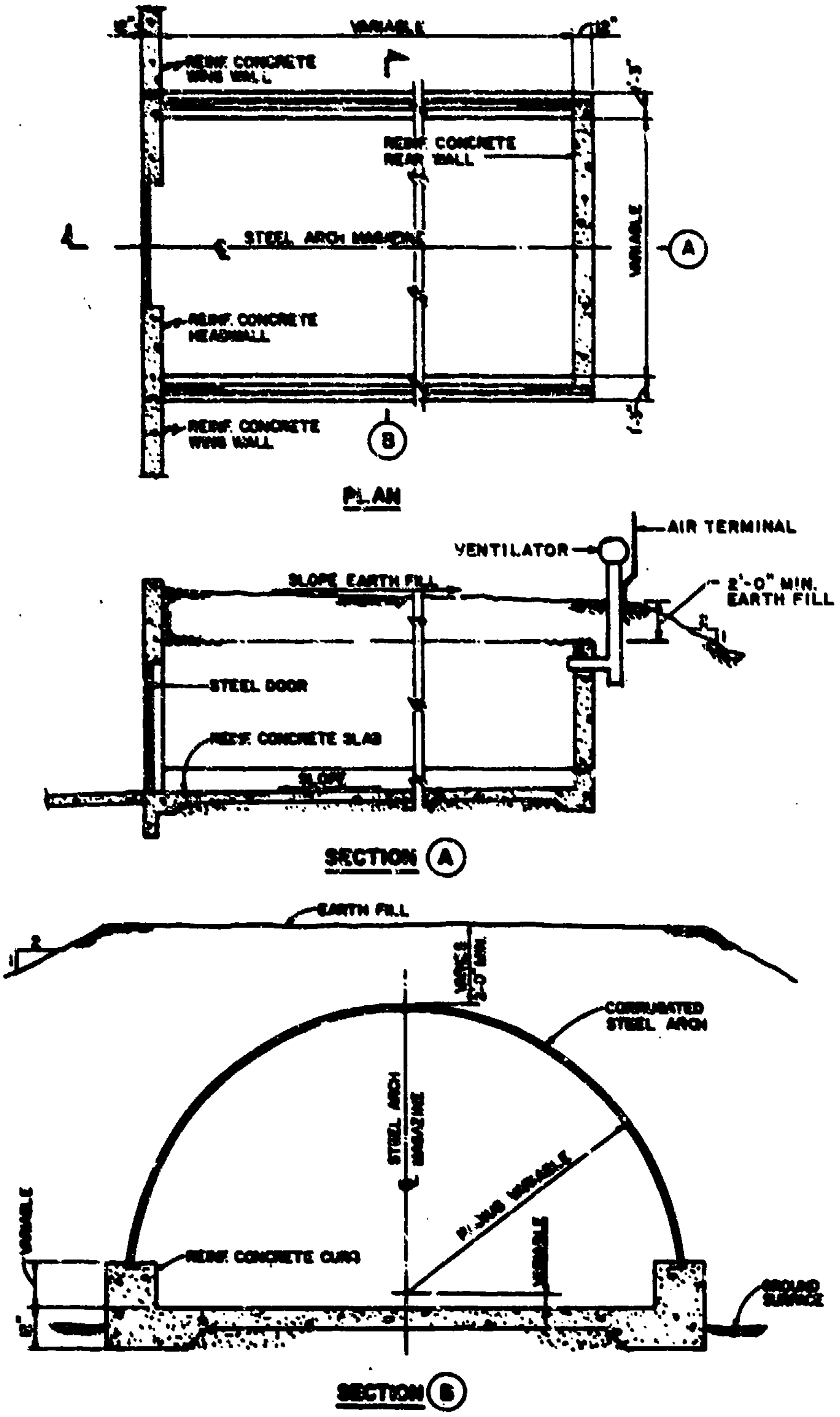
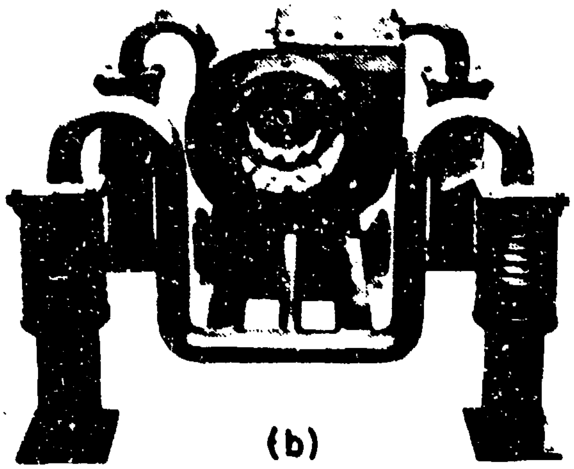
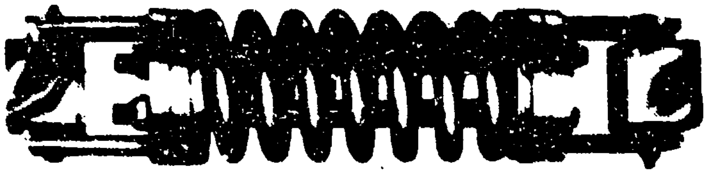


FIGURE 36 TYPICAL EARTH-COVERED STEEL-ARCH MAGAZINE

VERTICAL
SHOCK MOUNT



CENTER OF GRAVITY MOUNT PREVENTS
ROCKING UNDER SHOCK



HORIZONTAL SHOCK MOUNT

FIGURE 37 HELICAL COMPRESSION SPRING MOUNTS

EFFECTIVENESS OF TM 5-1300 CUBICLES ADDED TO EXISTING BUILDINGS:

A CASE HISTORY
MILAN ARMY AMMUNITION PLANT
LOAD ASSEMBLY AND PACK (LAP)
BUILDING A-2

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1.0 INTRODUCTION

On 1 April 1985 at approximately 8:20 a.m., an accidental explosion occurred at Milan Army Ammunition Plant (MAAP), Building A-2 of Line A. The source of the event was a feed hopper serving a grenade pressing operation. It was estimated that the feed hopper contained approximately 18 pounds of Composition A5. The pressing operation was located in a reinforced concrete cubicle located on the east side of the building. The incident caused the blowout failure of the frangible exterior wall of the adjacent service ramp, as well as the failure of a large area of the cement asbestos roofing over the main area of the building behind the cubicle. There was no significant structural damage to the building framing or the press cubicle. There were 45 operating personnel in the building at the time of the incident and only two minor injuries occurred, neither requiring hospitalization. Repairs of the building were completed by July 1985. This paper discusses the evaluation of the blast within the building and also the effects of the blast on the operating personnel.

Facility History

Building A-2 of Line A at MAAP is a 1940's vintage structure. It consists of steel roof trusses on steel columns as its main framing system, with a cement asbestos (transite) roof and clay tile block infill walls. The building was upgraded in 1980 to accommodate the 8-inch M509 Load Assembly and Pack (LAP) activity currently housed there. The principal elements in the building upgrade included the addition of reinforced concrete cubicles to house the hazardous press operations and enclosing exterior service ramps on both sides of the building. The press cubicles were designed in accordance with TM 5-1300 and were to provide protection to operating personnel from primary overpressure and fragment hazards originating in the press cubicle. Management of the design modification contract and technical review of the blast design was performed by The U.S. Army Engineer Division Huntsville (USAEDH).

Investigation

USAEDH was requested by MAAP to perform a damage assessment and structural integrity evaluation of the facility after the incident and to estimate the magnitude of the blast effects that personnel in the building may have been exposed to. To meet this objective, the following tasks were performed.

- Structural Damage Survey
- Prediction of Blast Effects
- Evaluation of Structural Integrity
- Assessment of Personnel Protection Provided

2.0 STRUCTURAL DAMAGE SURVEY

Overall Building

A detailed inspection of the overall condition of Building A-2 was performed within a few days of the incident. The results of this inspection were favorable to a relatively simple replacement of roofing and siding. Figure 2-1 presents a plan view of a portion of the Building 2-A, showing the area where the donor cubicle was located and designates the direction in which photographs presented as Figures 2-2 through 2-5 were taken. As can be seen in the pictures, the building damage was essentially limited to wall cladding and roof decking. The wall cladding on the east side of the ramp was intended to be a "frangible" or blowout-type wall designed to fail quickly and vent the shock and gas pressures from the adjacent cubicles. Figure 2-3 clearly shows large sections of the light weight frangible aluminum ramp wall panels which performed as intended. The bulk of the remaining damage was failure of the brittle transite roof decking material. The extent of this damage is exemplified in Figures 2-2 through 2-4. This material is very brittle and tends to break up into relatively small pieces under low overpressures. It should be noted that the roofing on the right side of Figure 2-4 had already been removed by repair crews and does not represent damage from the incident. The only damage to structural load carrying members involved two roof deck support beams directly in front of the donor cubicle. These members were twisted sufficiently that replacement was justified. With the exception of these members, the structural framing system was in excellent condition and immediately capable of accommodating the new wall and roof decking materials.

Press Cubicle

The donor press cubicle was designated No. 3 as shown in Figure 2-1. Figure 2-5 shows a frontal view of the cubicle looking west. This cubicle was designed in accordance with TM 5-1300 for 25 pounds of Composition A5. Close examination of the cubicle indicated that it was in excellent condition. There was no exterior spalling of any of the walls. There was a limited area of spall/scab on the exterior of the roof directly above the feed hopper location. This was a result of direct air blast shock being transmitted through the roof slab. However, the concrete spall was still attached to the roof as shown in Figures 2-6 and 2-7 and could not be broken loose without the use of tools. While flexure tensile cracks were observed as expected for an internal explosion, they were not extensive or large in size. Figures 2-8 through 2-11 show some of these typical cracks. Stringline measurements revealed that only very limited inelastic deformation had occurred and only within a short distance near the open end of the cubicle. There was absolutely no evidence of any compression zone distress of the concrete section that indicated significant damage. The fact that observed tensile crack patterns had not formed classical yield line patterns further suggested very limited response. Following the initial inspection, the cubicle walls were sandblasted to remove paint, filler, and sealant. The appearance of the cubicle after sandblasting was consistent with the initial observations. In addition, the spall/scab area on the roof was removed until sound concrete was reached. Internally, the principal damage to the cubicle was cratering due to high velocity primary fragments from the press tooling. The main cratering damage was localized over several well-defined regions as shown in Figures 2-12 and 2-13. The maximum depth of these spall craters did not exceed 2 inches in any location and were generally much less. It was judged, based on the initial inspection, that the cubicle could be repaired using epoxy grouts or high strength mortars. This evaluation was confirmed by analysis based on material properties obtained from nondestructive testing of the actual cubicle.

3.0 PREDICTION OF BLAST EFFECTS

Loads on the Building

The principal damage to the building system was the destruction of the cement asbestos roofing. This was also the primary area of concern regarding hazards to which operating personnel were exposed. Therefore, the main emphasis in estimating the air blast effects from the incident will be determining the loads to which the roof and the personnel behind the cubicle were subjected. The determination of probable overpressure loads on the building will be based on air blast parameters given in TM 5-1300 (Reference 1) and the methodolgy developed in Reference 2 by Keenan at the Naval Civil Engineering Laboratory (NCEL). This approach has the merit of having been confirmed in part from the testing of an actual building of nearly identical construction to Building A-2 (Reference 3). The analysis procedure provides for a modification of the scale distance from a donor charge in a cubicle to a receiver. This method accounts for the effect of the cubicle walls and roof in increasing the scale distance from the donor to the receiver.

The location of the feed hopper in the cubicle was such that there was some question as to whether the donor charge should be considered a free air burst or a surface burst, the latter being fully reflected. Air blast parameters for the two cases are given respectively in Figures 4-5 and 4-12 of Reference 1. Because of this question, both situations are considered and estimated overpressure calculated for each. Tables 3-1 and 3-2 show the geometric data and resulting air blast parameters for the estimated overpressures on the roof and also at an elevation of 5 feet above the floor (for effects on a standing adult). Figure 3-1 presents these same results as expected upper and lower bounds of overpressure for the roof and the interior of the building respectively. Figure 3-2 shows the idealized path of the blast wave over the building. There is another path which must also be considered and it is shown in Figure 3-3. The results of this load path were found to be no more severe than those of Figure 3-2 and therefore, were not further considered. The building tested in Reference 3 had a roof deck of transite nearly identical to the Milan Building A-2. The estimated dynamic capacity of the roof decking in that test was about 6 psi for short duration impulsive loadings. Since The Milan Building A-2 deck is a slightly longer span, it would be expected to fail at a slightly lower load. Predicting the decking failure load at Milan to be approximately 4.5 psi, the information in Figure 3-1 suggests that roof deck within about 30 feet of the cubicle would probably fail. This was consistent with observed damage as shown in Figures 2-2 through 2-4.

Blast Loads Within the Cubicle

The blast environment inside the donor cubicle is also calculated based on the information in Reference 1. The cubicle has one entire wall open to the adjacent service ramp and the ramp was designed with a frangible exterior wall. As a consequence, gas pressure is not a consideration and only shock pressures need be considered. The estimated air blast environment within the cubicle is presented in Table 3-3. The information shown is similar to the same data in Reference 3 for a similar magnitude donor.

4.0 ASSESSMENT OF REMAINING STRUCTURAL CAPACITY

Building Structural System

Upon completion of the damage survey and the initial evaluation that the building structural framing system was undamaged and suitable for reuse, a new lightweight aluminum roof decking was installed. This decking was used in place of the former cement asbestos decking which had the undesirable trait during failure of generating large amounts of secondary free falling fragments. However on the beneficial side the low failure capacity of the transite assured that significant dynamic loads would not be imposed on the roof deck support beams (purlins) or the main building framing. The new aluminum decking has a very low load capacity when it was limited to a two span configuration. However the decking as actually installed covered four spans. This results in the two interior spans being capable of developing large deflection membrane resistance after the low flexure capacity is exceeded. It was therefore necessary to assure that the roof purlins were capable of resisting the new loads. Using the upper bound overpressures determined previously for the roof, a conservative analysis based on References 1 and 4 confirmed that the roof purlins and trusses could safely resist a similar incident in the future.

Press Cubicle

Dynamic analyses of the press cubicle walls and roof were performed based on Reference 1. The concrete strength used in the analysis was based on the results of the actual in-place compressive strength of the cubicle concrete as determined by nondestructive testing performed in Reference 5. The measured compressive strength values are given in Table 4-1 and exhibit the increase in strength with age that is typical of quality concrete. The dynamic stuctural properties of the cubicle are given in Table 4-2. The results of these analyses in terms of predicted maximum deflections and actual measured values at midspan of walls and roof are shown in Table 4-3. It should be noted that the presence of tensile steel at the middepth of the concrete elements has a significant influence in limiting the maximum deflection. This steel is normally neglected when designing for flexure. The measured deflections reflect only localized permanent deflections near the open end of the cubicle. The ductility ratios associated with these deflections are within the range considered to be acceptable for reusable structures in Reference 1. Repair of the spall damage with a quality epoxy grout will provide a cubicle which is capable of resisting a similar incident safely in the future.

5.0 EVALUATION OF PERSONNEL PROTECTION

The Milan A2 building was an upgrade of an old structure to accommodate a new process with a hazardous operation. The economics of the project did not allow for hardening the entire building for personnel protection nor did safety policy at the time require such action. However the use of cubicles with hardened roofs and frangible vent walls on the ramp adjacent to the open wall of the cubicle were used to provide the highest feasible level of protection for a building of this type. Hazards to personnel include overpressure, primary fragments and secondary fragments. Primary fragments were either confined or directed safely away by the cubicle and were not a consideration for personnel in Building A-2. Overpressure can result in several types of hazard and these will be discussed individually as will secondary fragments.

Primary Blast Effects

Primary blast effects on the human body are related to peak overpressure and specific impulse of the blast wave. The lungs are the most susceptible organs in the body when considering primary blast effects. Figure 5-1 presents data which allows evaluating the risk of lung damage based on incident overpressure and impulse. These curves are extracted from References 6 and 7. Shown also on the same figure is the scaled overpressure and impulse based on the upper bound values in Table 3-2. These calculations were based on an assumed body weight of 130 pounds. The results are plotted on the figure and show clearly that for the predicted blast environment in the work area of Building A-2, the risk of lung damage is negligible.

Tertiary Blast Injury

The term "Tertiary Blast Injury" refers to injuries resulting from whole body displacement. Tables 5-1 and 5-2 present criteria for risk of injury to either the skull or the whole body due to impact at the velocities shown. Although the skull injury tolerance is generally lower, both criteria have the same lower limit "mostly safe" velocity. Figure 5-2 presents the critical velocities in Table 5-1 in terms of incident pressure and impulse. Plotted on this figure is again the upper bound data from Table 3-2. Results show clearly that translational forces for the Milan incident appear to be well below those needed to cause a critical velocity.

Ear Drum Damage

The human ear is the most sensitive part of the body when considering the effects of a blast wave. An incident overpressure of 5 psi arriving normal to the ear represents the threshold for eardrum rupture. Even lower pressures can cause temporary loss of hearing. The generally accepted "Temporary Threshold Shift" (TTS) is about 2.3 psi (Reference 8). These values and the 50 percent rupture pressure are plotted on Figure 5-3 in terms of incident overpressure and impulse, along with the upperbound data from Table 3-2. This indicates that a risk of at least temporary hearing loss and the onset of eardrum rupture existed at Milan if the head were oriented side-on to the blast wave.

Secondary Fragment Impact

Risks of injuries due to secondary fragment effects at Milan were due almost entirely to the break up of the transite roof decking and it's falling into the work area behind the cubicle. Figure 5-4 presents criteria developed in Reference 9 for injuries to personnel from secondary fragments. Risk of injury is a function of impact velocity and fragment mass. It should be noted that the lower threshold for injuries from fragments greater than 3 pounds is identical to that for tertiary injury given earlier in Figure 5-2. The height of the transite roofing above the work area floor varies from about 11 feet at the exterior walls to 21 feet at the center of the building. Assuming unobstructed free fall and neglecting drag, Table 5-3 presents free fall times and velocities from the roof to the floor and from the roof to 5 feet 6 inches above the floor respectively. Although a great percentage of the roofing broke into small pieces, i.e., less than 2 or 3 pounds, there were sizeable numbers of larger fragments present. Based on the potential free fall velocities from the Table 5-3 and the criteria in Figure 5-4, there appears to have been a risk of injury from secondary fragments. The minimum risk appears to exist for personnel in the upright position which reduces both the abdominal, thorax, and limb exposure, as well as the probable head injury velocity. Based on the velocities calculated, any fragment larger than 2 pounds would pose a risk. It is interesting to note that a fragment falling from the highest elevation of the roof would have to weigh at least 3.7 pounds to exceed the 58 foot-pound hazardous fragment as defined in DOD 6055.9 (Reference 10) which is the most current relatable safety criteria. It should also be noted that the space below the roof and above the work area is very congested with ventilation ducting, piping, conduit and other items, none of which fell. These items would tend to obstruct the unimpeded free fall of fragments, particularly large ones. This effect may have contributed to the lack of actual fragment-impact injuries.

6.0 SUMMARY

Original Design Safety Criteria

The original criteria used in the modification of the building called for protection of personnel from primary blast and fragment effects (Reference 11). Original criteria also proposed a three-wall cubicle with a venting roof. During review of the criteria (Reference 12), comments were made by USAEDH regarding protection which such a cubicle was capable of providing to personnel in the building. It was recommended that the cubicles be designed with a hardened roof since this would substantially reduce the overpressures to which the building behind the cubicle would be subjected. However, it was also commented that even a hardened roof would not reduce overpressures on the transite roof sufficiently to preclude failure of the decking. The recommendation for adding the hardened roof to the design was incorporated into the criteria. The comments regarding roof deck failure were acknowledged but fiscal constraints resulted in retaining the existing roof. The philosophy followed and accepted during the safety review was to obtain the highest possible level of protection within the limitations of the existing building structural system.

Actual Performance of the Building

The performance of the cubicle was as expected in the original design. All primary blast and fragments were directed safely away from the operating areas and the hardened roof reduced overpressures behind the cubicles sufficiently to eliminate essentially all risks other than threshold eardrum rupture and secondary fragments. It is significant to note that if the original concept of a three-wall cubicle with a venting roof had been used, the peak overpressure on the roof and behind the cubicles would have 17 and 11 psi, respectively, and both damage and risk of injury would have increased substantially. The actual performance was also aided by the fact that the quantity of explosive involved was less than the quantity called for in the design criteria. In addition, the actual concrete strength had increased substantially above the original specified value. In any case the cubicle with a hardened roof is superior to one with a venting roof in terms of reducing pressures behind the cubicle. The overpressures and cubicle shock loads calculated in this analysis agree quite well with observed damage at Milan and are also in good agreement with measured data from the full scale building test of Reference 3.

Personnel Protection

The most current governing criteria for personnel protection is defined in Reference 10. This guidance requires personnel be protected from fragments exceeding 58 foot-pounds of energy and overpressure exceeding 2.3 psi. This guidance did not govern at the time the Milan design and construction were performed. Although not in compliance with this more recent criteria, the Milan building and cubicles do in effect provide a high degree of protection for operating personnel. The new aluminum roof will essentially eliminate the secondary fragment risk experienced in this accident. The most likely remaining risk to personnel will continue to be that of temporary threshold shift and possible eardrum rupture.

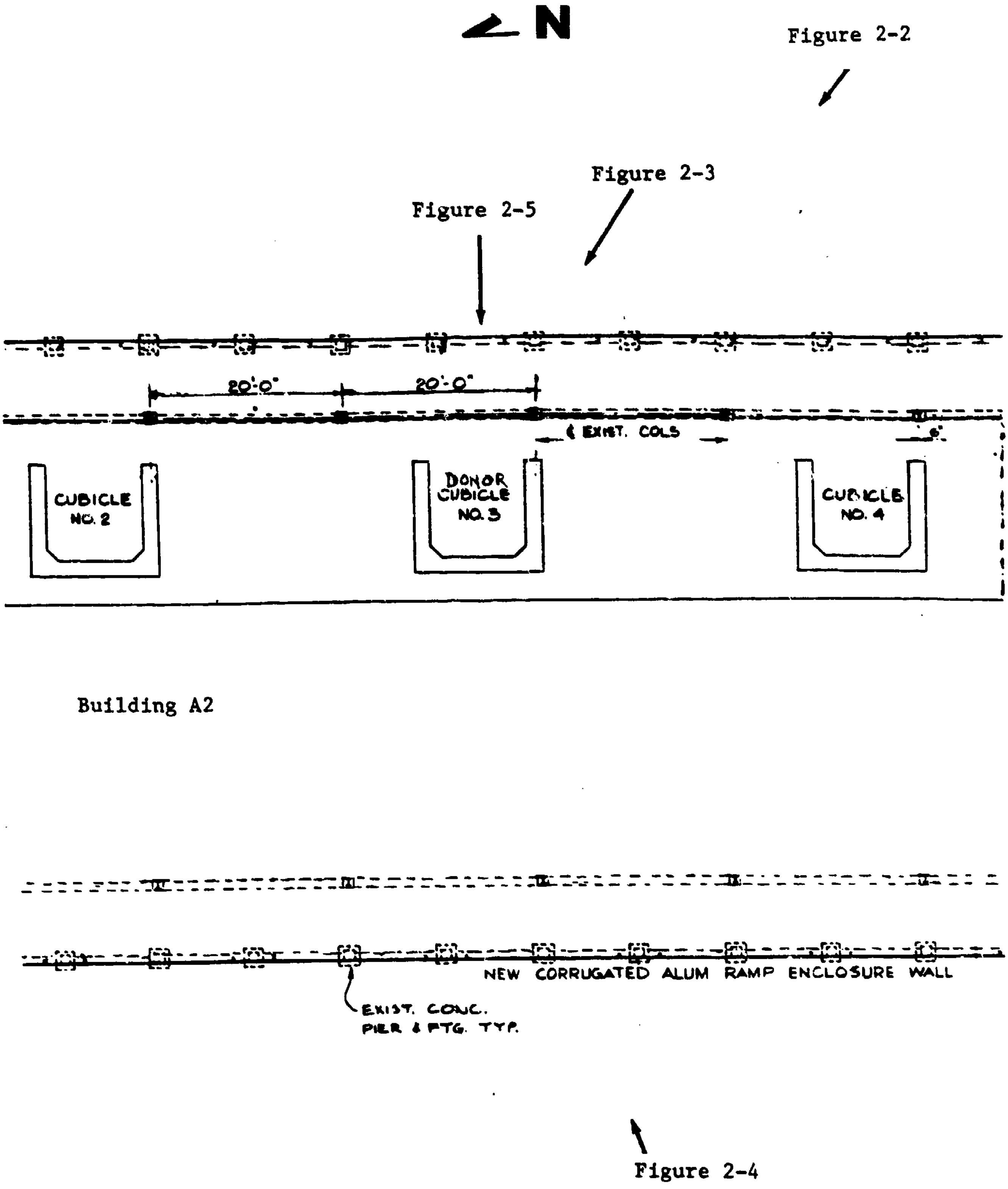


Figure 2-1. Plan View of a Portion of Building A2

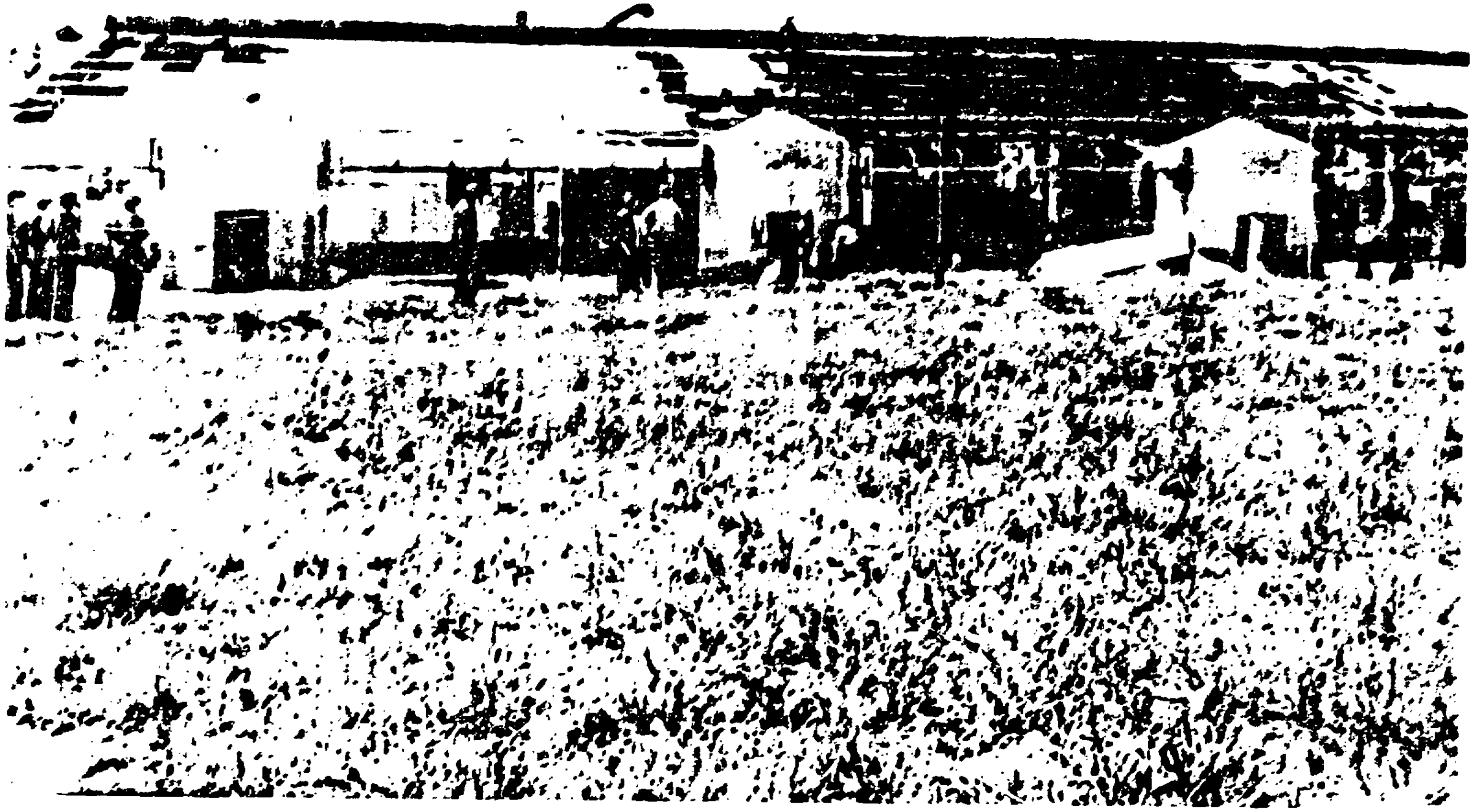


Figure 2-2. East Elevation of Overall Building

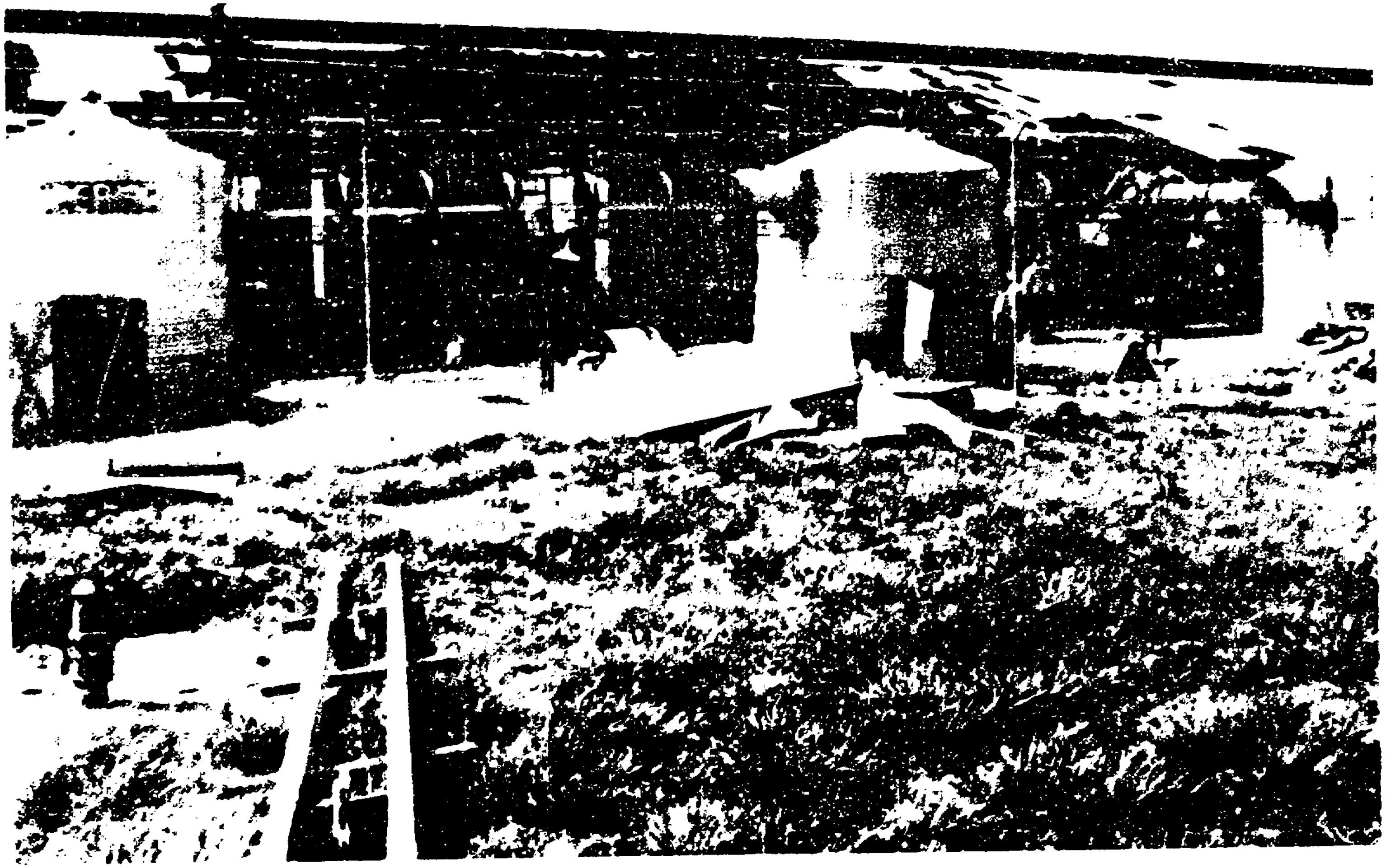


Figure 2-3. East Elevation Ramp Damage

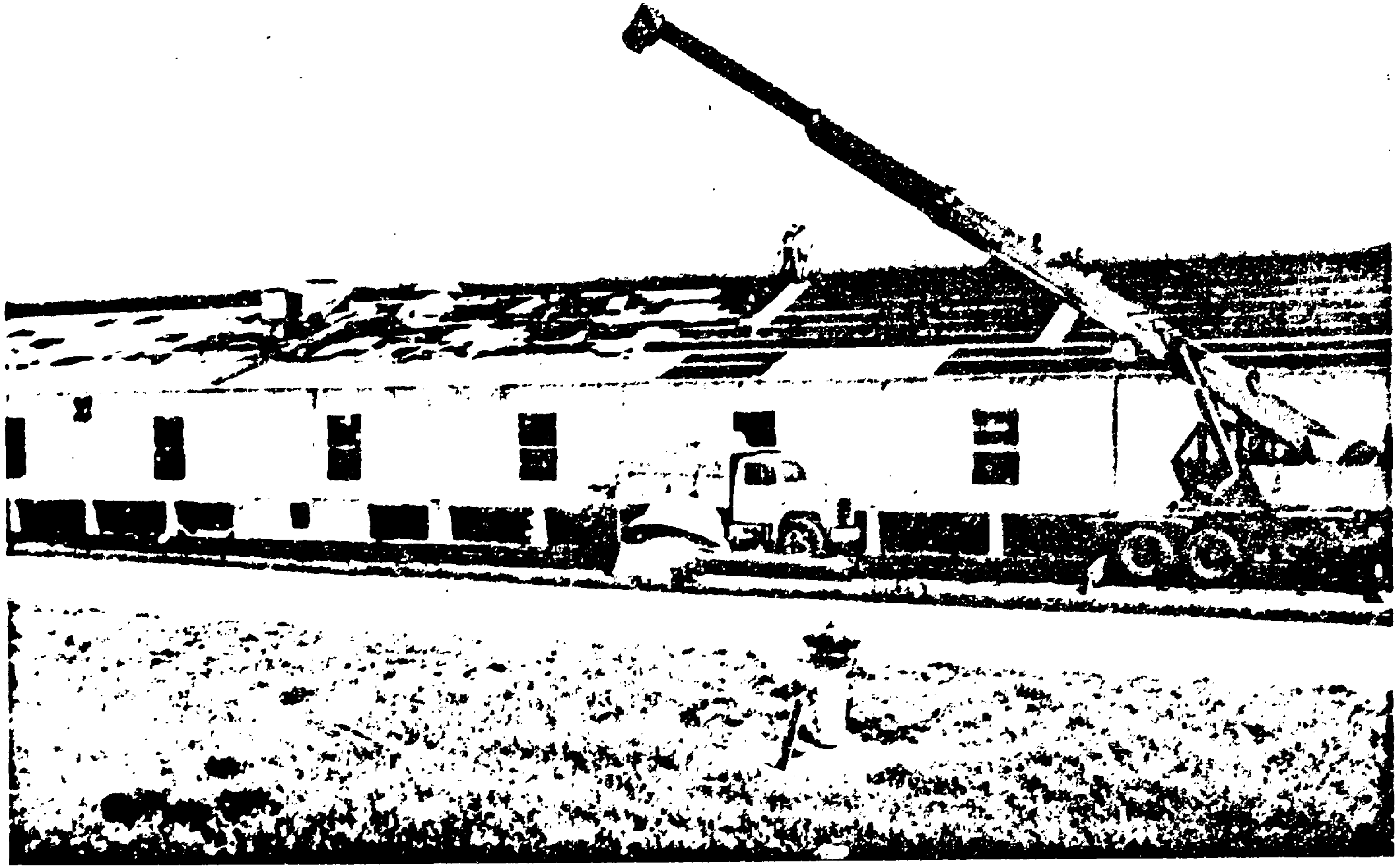


Figure 2-4. West Elevation of Overall Building

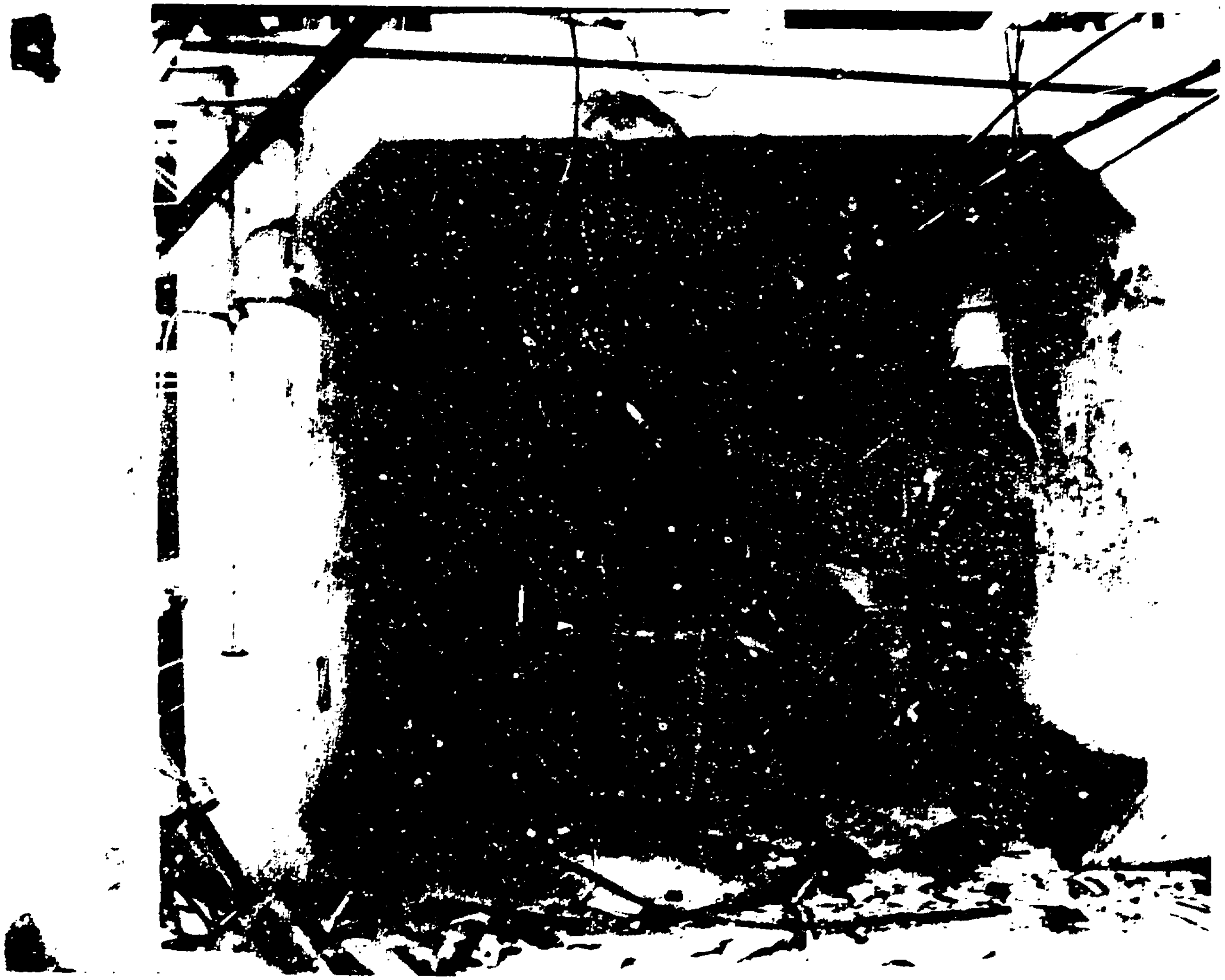


Figure 2-5. Donor Cubicle

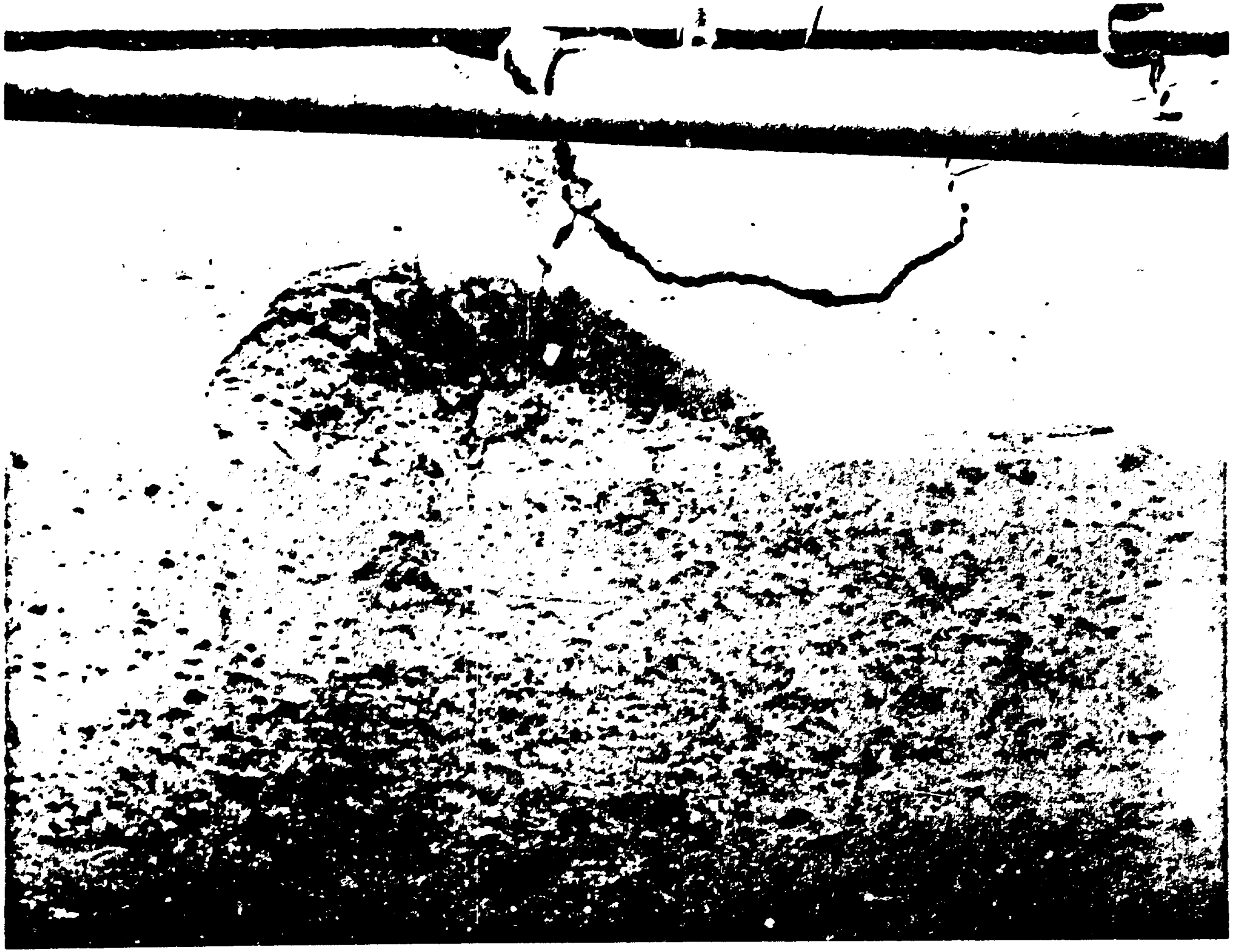


Figure 2-6. Edge of Roof Slab Donor Cubicle

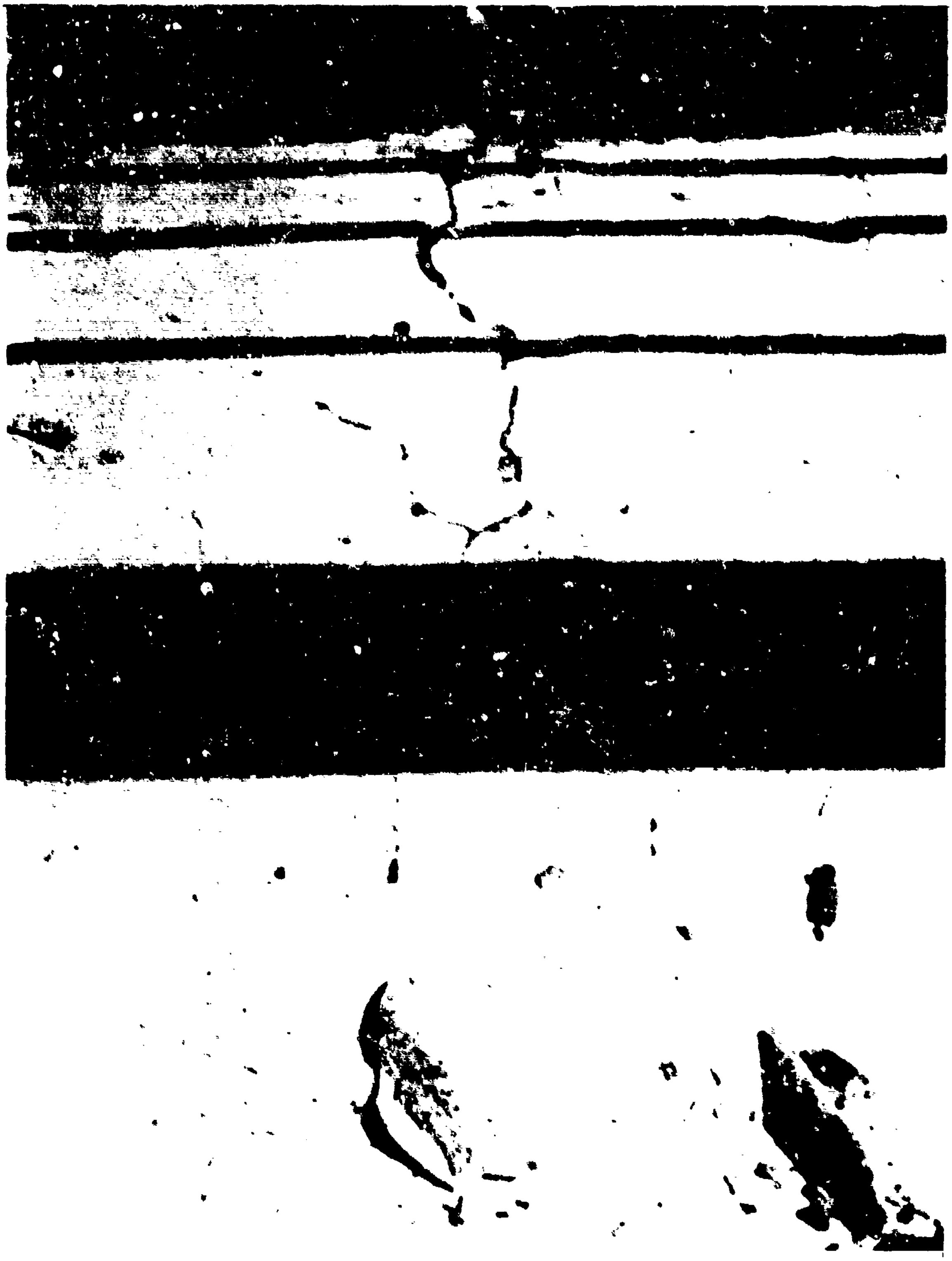


Figure 2-7. Cubicle Roof Looking East

Figure 2-8. Left Wall

Figure 2-9. Right Wall

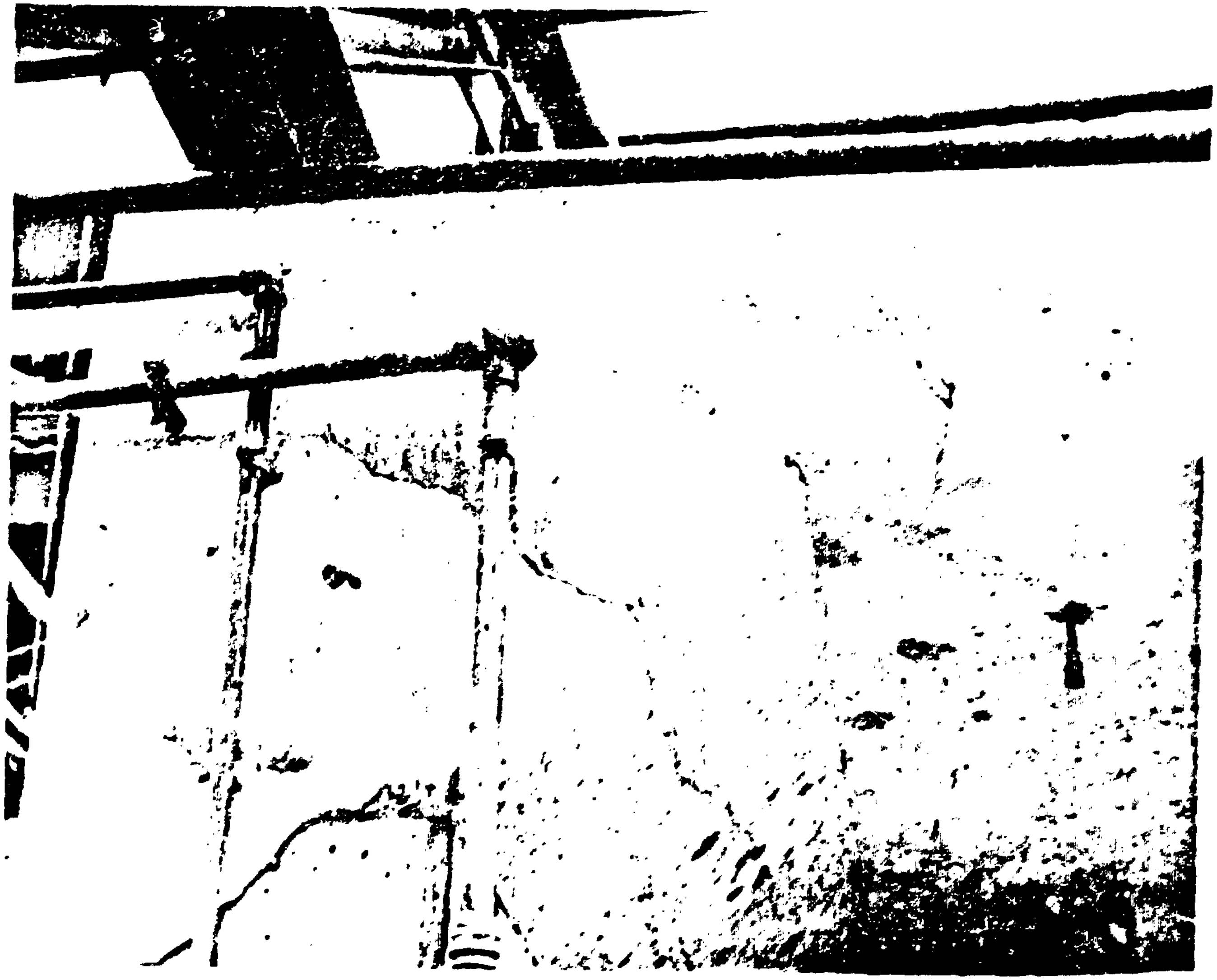


Figure 2-10. Upper Haunch Left Wall

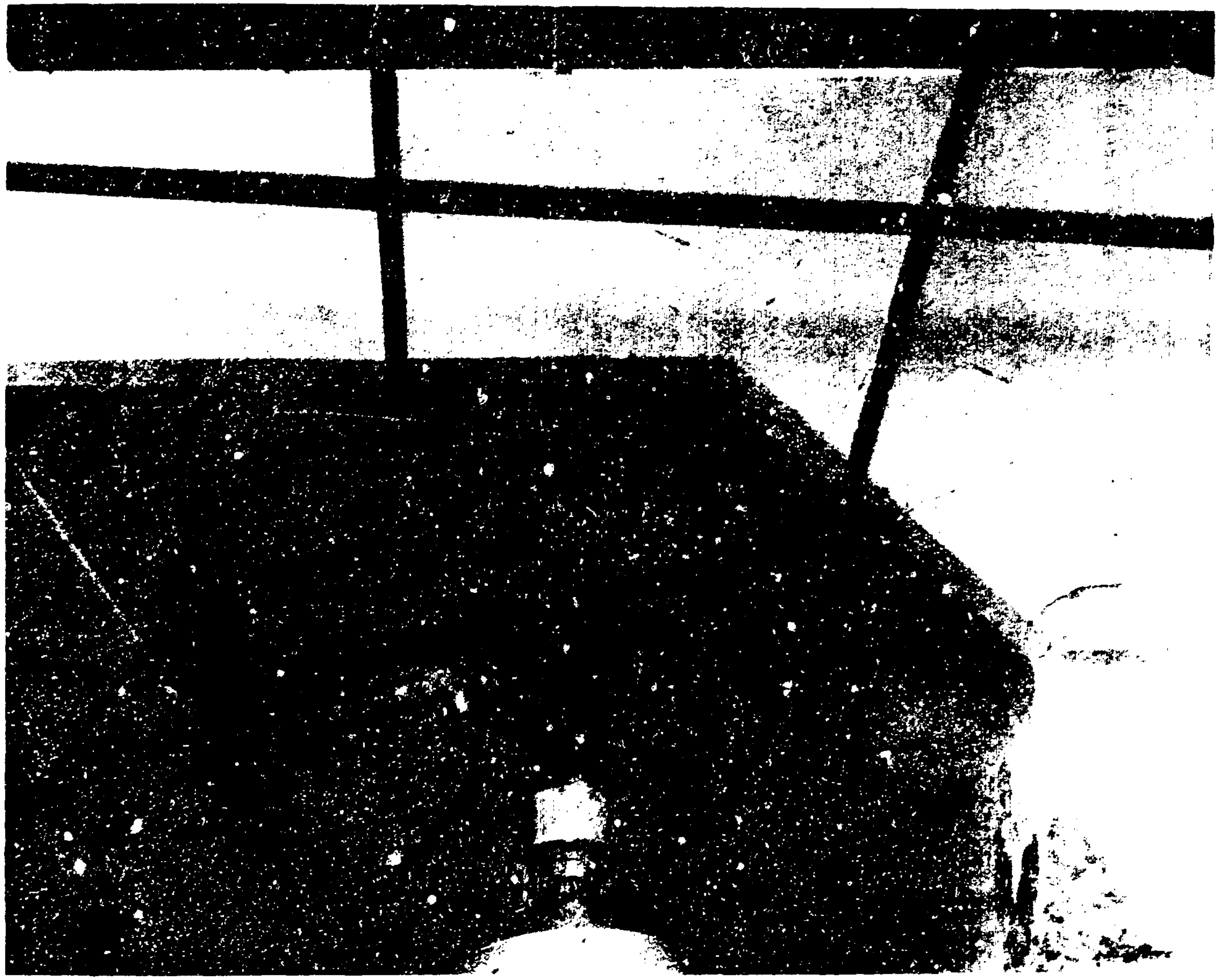


Figure 2-11. Upper Haunch Right Wall

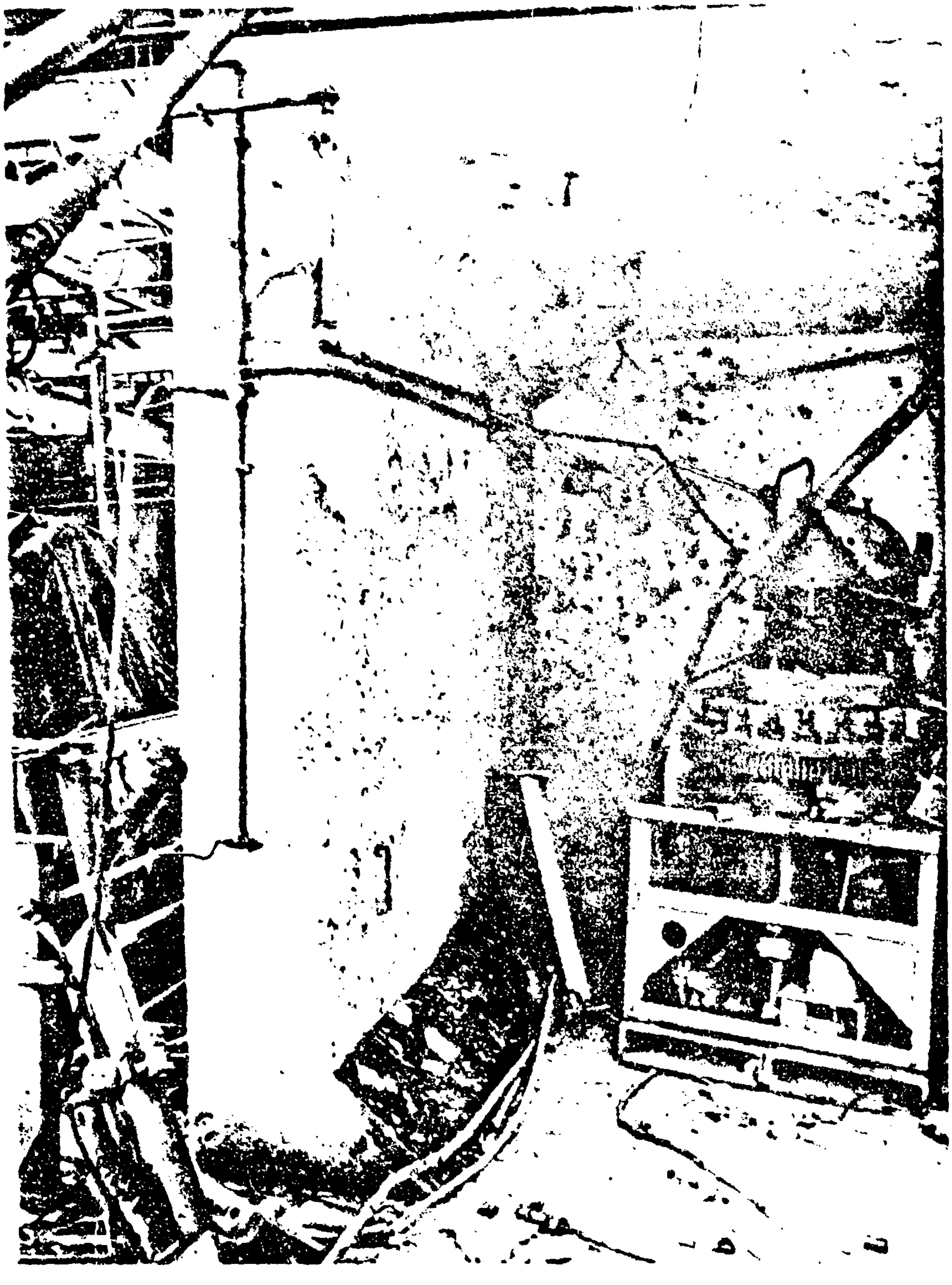


Figure 2-12. Interior Fragment Damage Left Wall

Figure 2-13. Interior Fragment Damage Right Wall

Table 3-1. Airblast Loading on Roof
(see notes)

$W^{1/3}=2.71$

ROOF(1) LOCATION	R'(2) (FT)	Z $R/W^{1/3}$	AIRBURST(3)			SURFACE BURST(4)		
			P_{so}	T_o	I_s	P_{so}	T_o	I_s
R-1	27	10.0	6.7	5.6	16.7	9.5	6.0	26.4
R-2	35	12.9	4.2	6.4	13.9	6.5	7.2	20.8
R-3	47	17.4	2.7	7.5	10.8	4.0	8.3	16.7
R-4	58	21.4	2.2	8.1	8.9	2.7	9.2	13.6

Table 3-2. Airblast Loading 5 Ft Above Floor
(see notes)

FLOOR(1) LOCATION	R'(2) (FT)	Z $R/W^{1/3}$	AIRBURST(3)			SURFACE BURST(4)		
			P_{so}	T_o	I_s	P_{so}	T_o	I_s
F-1	38	14	3.5	6.8	11.6	5.0	7.3	18.9
F-2	38	14	3.5	6.8	11.6	5.0	7.3	18.9
F-3	45	16.6	2.5	7.3	10.0	3.9	8.4	16.2
F-4	54	20	2.3	7.6	8.6	2.7	9.2	12.9

NOTES:
1. See figure 3-1 for locations
2. R'=effective distance determined per reference 2
3. From figure 4-5 of reference 1
4. From figure 4-12 of reference 1

UNITS: P_{so}=(PSI) T_o=(msec) I_s=(PSI-msec)

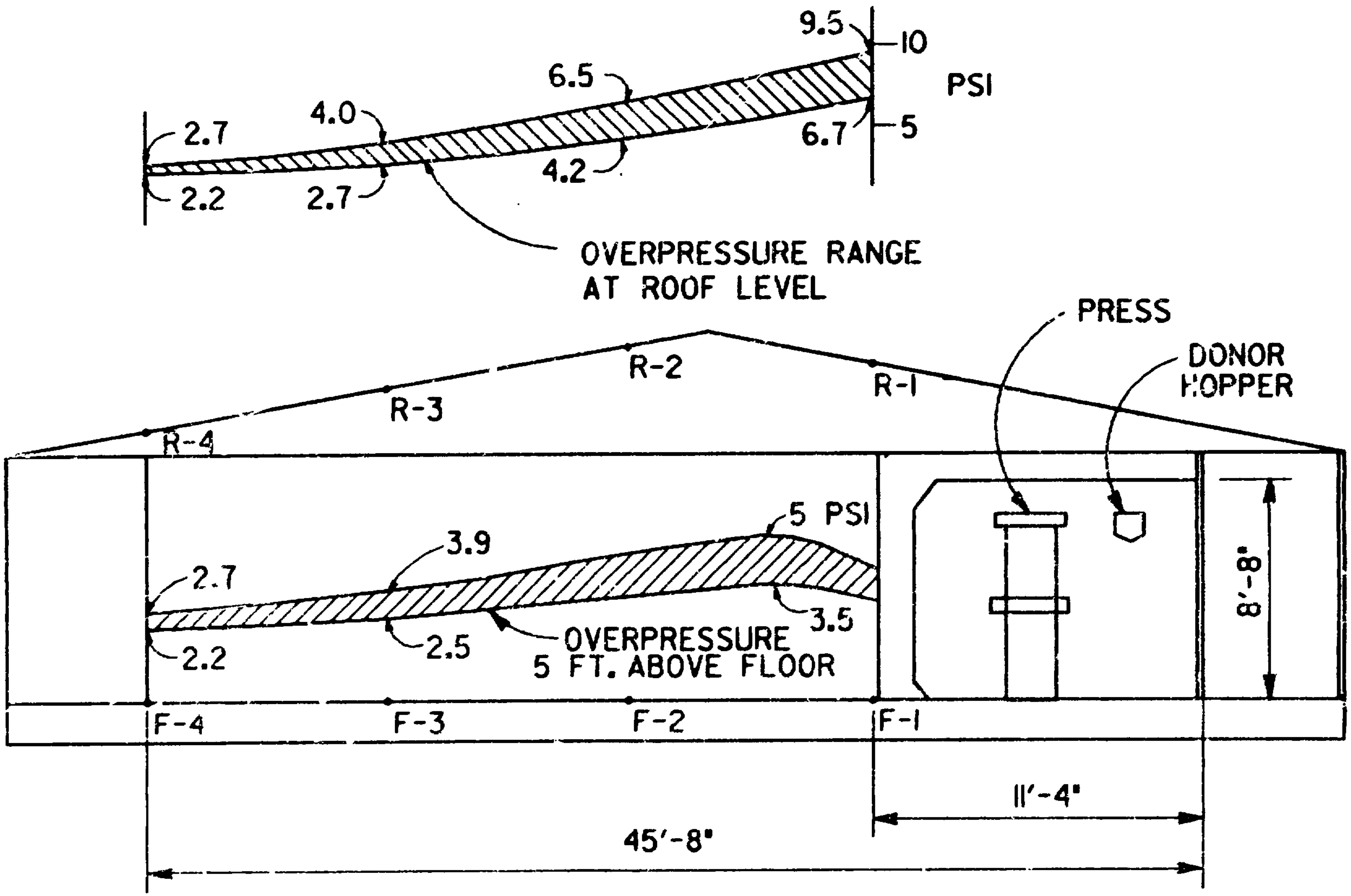


Figure 5-1. Milan Line A Donor Cubicle Overpressures

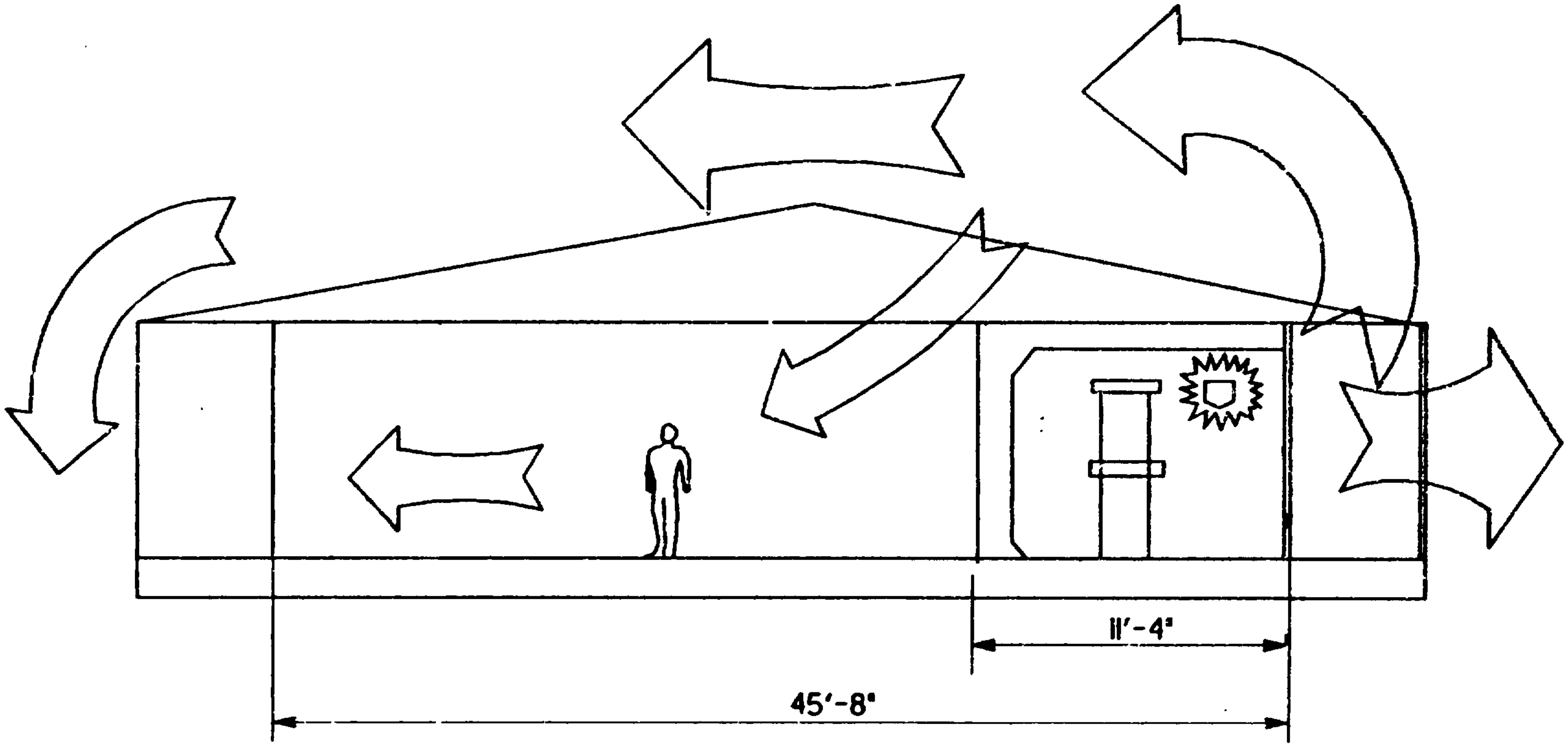


Figure 3-2. Milan Line A Donor Cubicle Blast Path

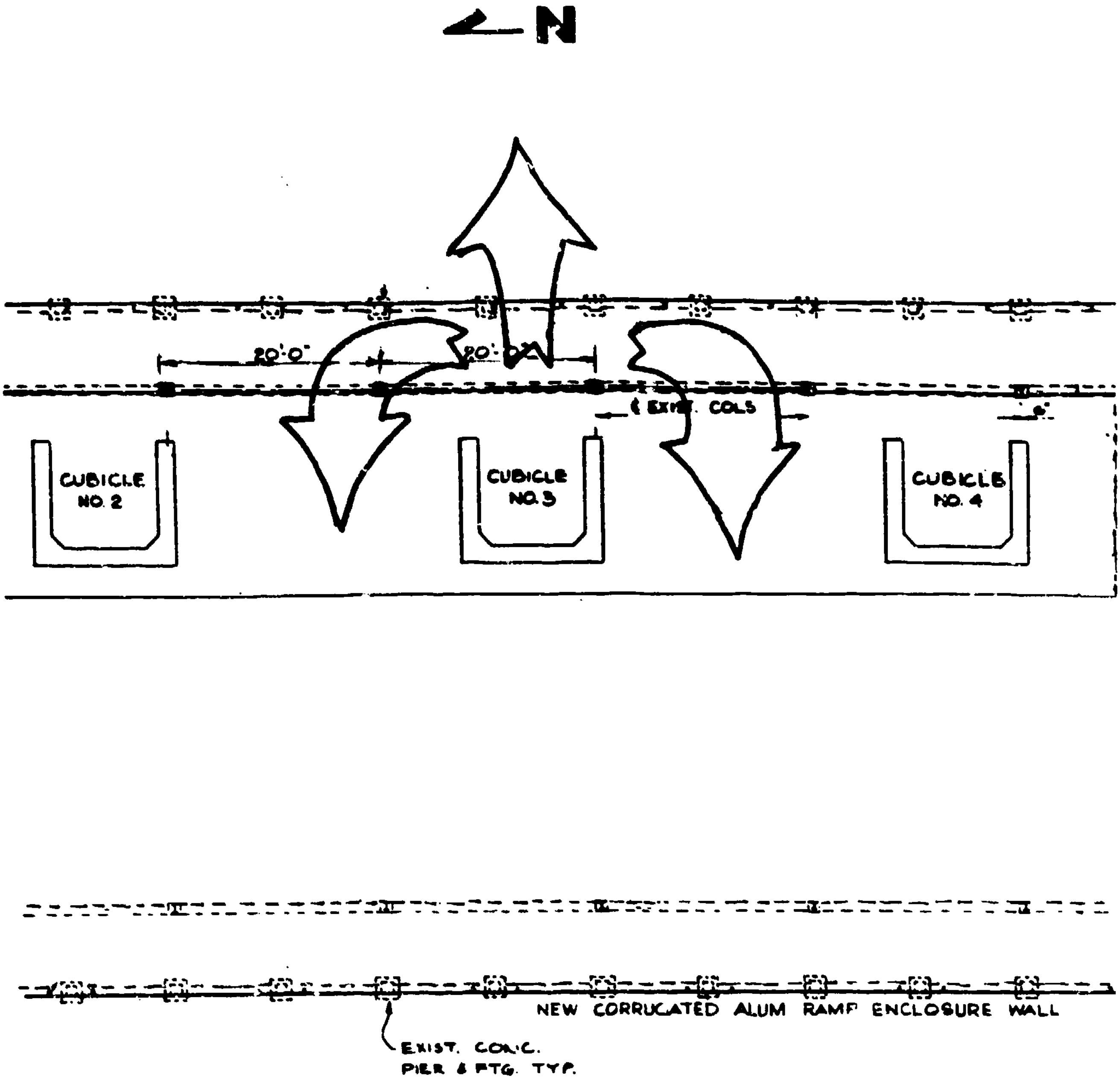

N
20'-0"
20'-0"
℄ EXIST. COLS
CUBICLE NO. 2
CUBICLE NO. 3
CUBICLE NO. 4
NEW CORRUGATED ALUM RAMP ENCLOSURE WALL
EXIST. CONC. PIER & FTG. TYP.

Figure 3-3. Blast Path Exterior to Cubicle

Table 3-3. Blast Environment Within Cubicle

CUBICLE LOCATION (1)	PARAMETER (2)		
	IMPULSE (PSI-ms)	PRESSURE (PSI)	DURATION (msec)
ROOF	566	313	3.6
SIDEWALLS	600	331	3.6
REAR WALL	600	262	4.6

Table 4-1. Measured Compressive Strength (PSI) (reference 5)

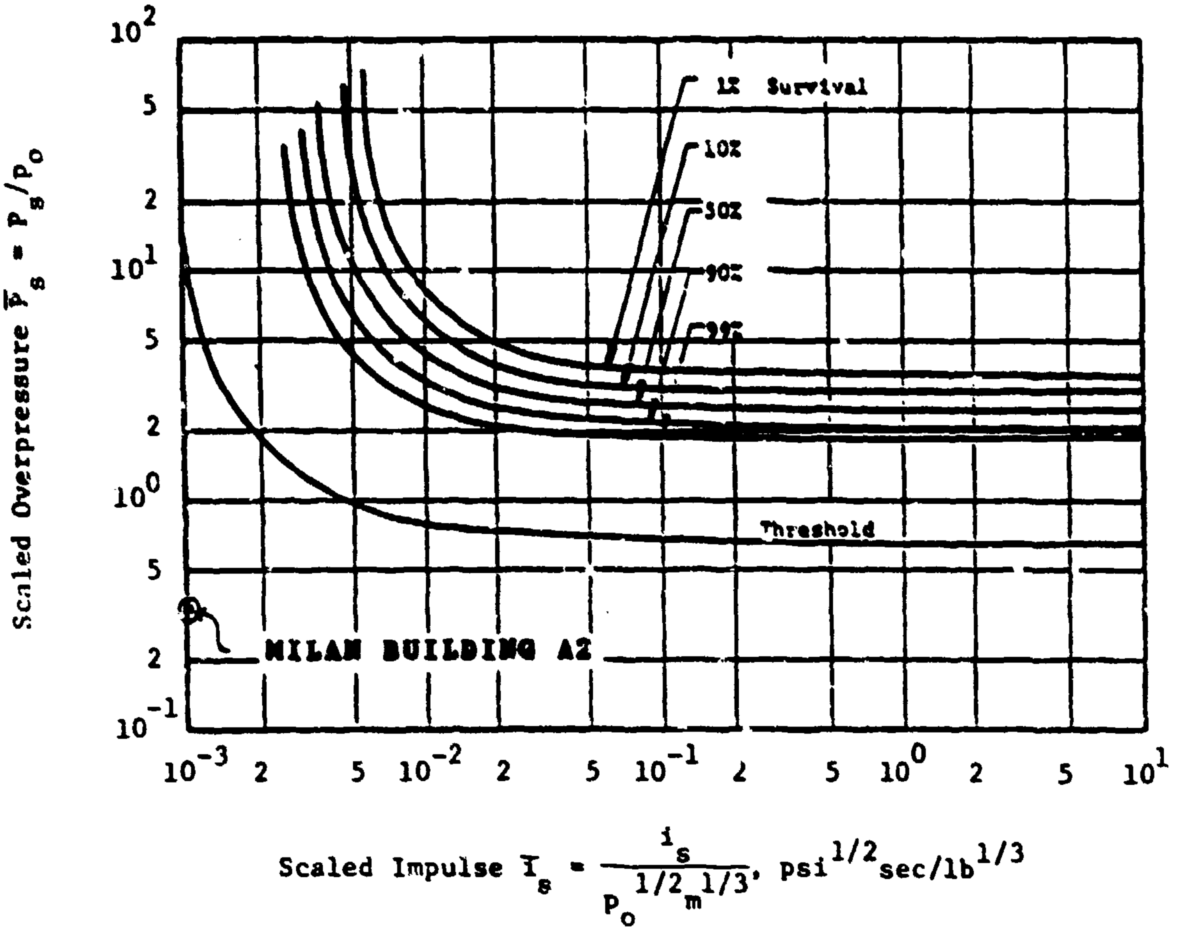
LOCATION	LOWER	MIDDLE	UPPER
LEFT WALL	6870	7000	7000
RIGHT WALL	6155	7460	7000
REAR WALL	6285	7240	7000
ROOF	7000	7000	7000

Table 4-2. Cubicle Dynamic Properties

CUBICLE SURFACE	NATURAL PERIOD (msec)	ULTIMATE RESISTANCE (PSI)	STIFFNESS K_e (LB/IN)	MASS M_e ($LB\text{-}ms^2/IN$)
SIDEWALL	5.36	209	3354	2438
ROOF	7.8	169	1462	2271
REAR WALL	5.1	177	3185	2108

Table 4-3. Response

CUBICLE SURFACE	CALCULATED			MEASURED
	2-DEGREE DEFL (IN)	ELASTIC DEFL (IN)	MAXIMUM DEFL (IN)	MAXIMUM DEFL (IN)
SIDEWALL	1.4	0.060	0.221	0.156
ROOF	1.8	0.055	0.236	NONE
REAR WALL	1.68	0.115	0.344	0.25



MILAN BLDG A2 $\overline{Ps} = 0.340$

$\overline{is} = 0.001$

Figure 5-1. Survival Curves for Lung Damage to Man

Table 5-1. Criteria for Tertiary Damage (Decelerative Impact) to the Head (reference 8)

SKULL FRACTURE TOLERANCE	IMPACT VELOCITY FT/SEC
MOSTLY "SAFE"	10
THRESHOLD	13
50 PERCENT LETHALITY	18
NEAR 100 PERCENT LETHALITY	23

Table 5-2. Criteria for Tertiary Damage Involving Total Body Impact (reference 8)

TOTAL BODY IMPACT TOLERANCE	IMPACT VELOCITY FT/SEC
MOSTLY "SAFE"	10
LETHALITY THRESHOLD	21
50 PERCENT LETHALITY	54
NEAR 100 PERCENT LETHALITY	138

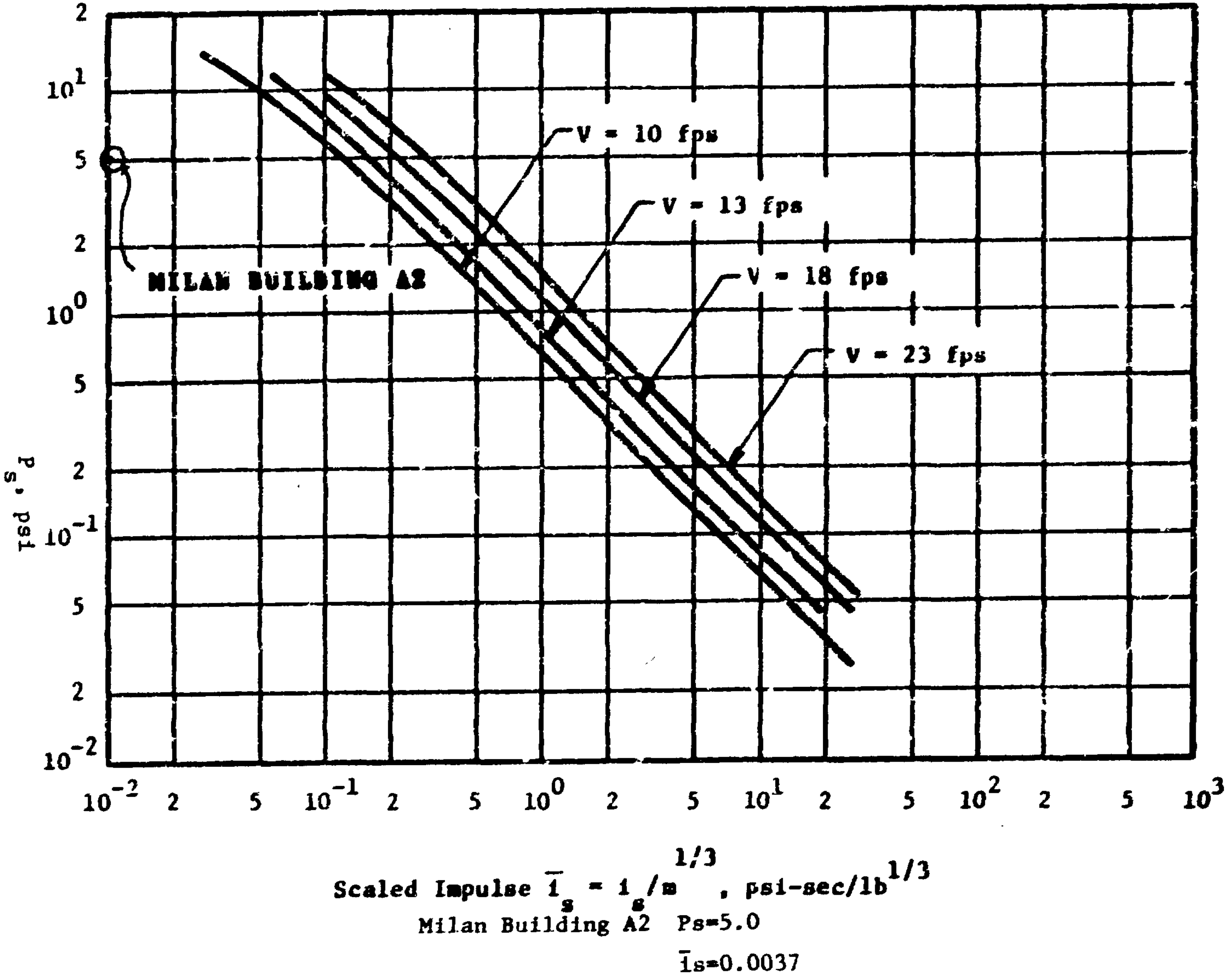
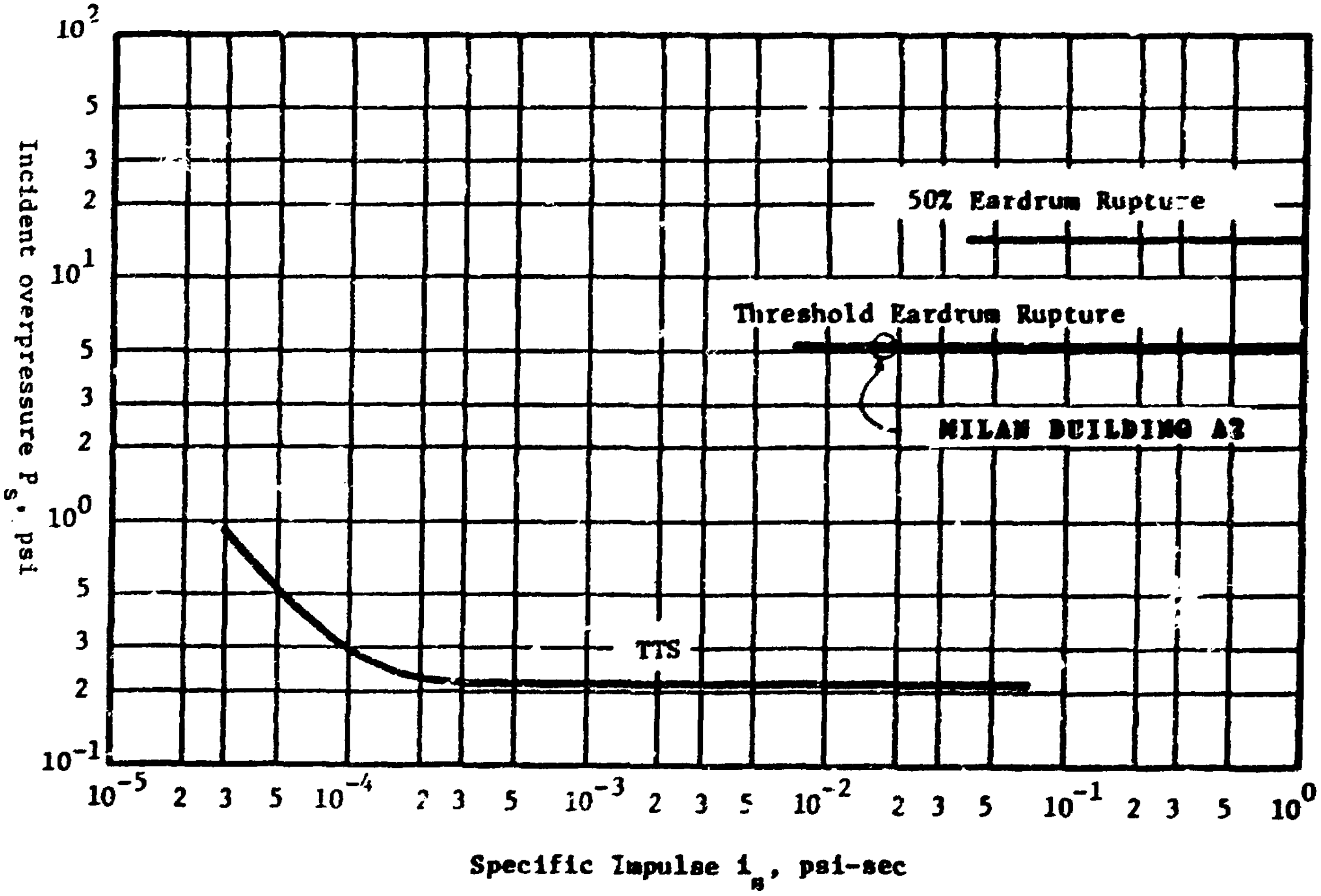


Figure 5-2. Skull Fracture Risk (reference 8)



Milan Building A2 Ps=5.0

is=0.0189

Figure 5-3. Human Ear Damage Risk for Normal Incidence Blast Waves (reference 8)

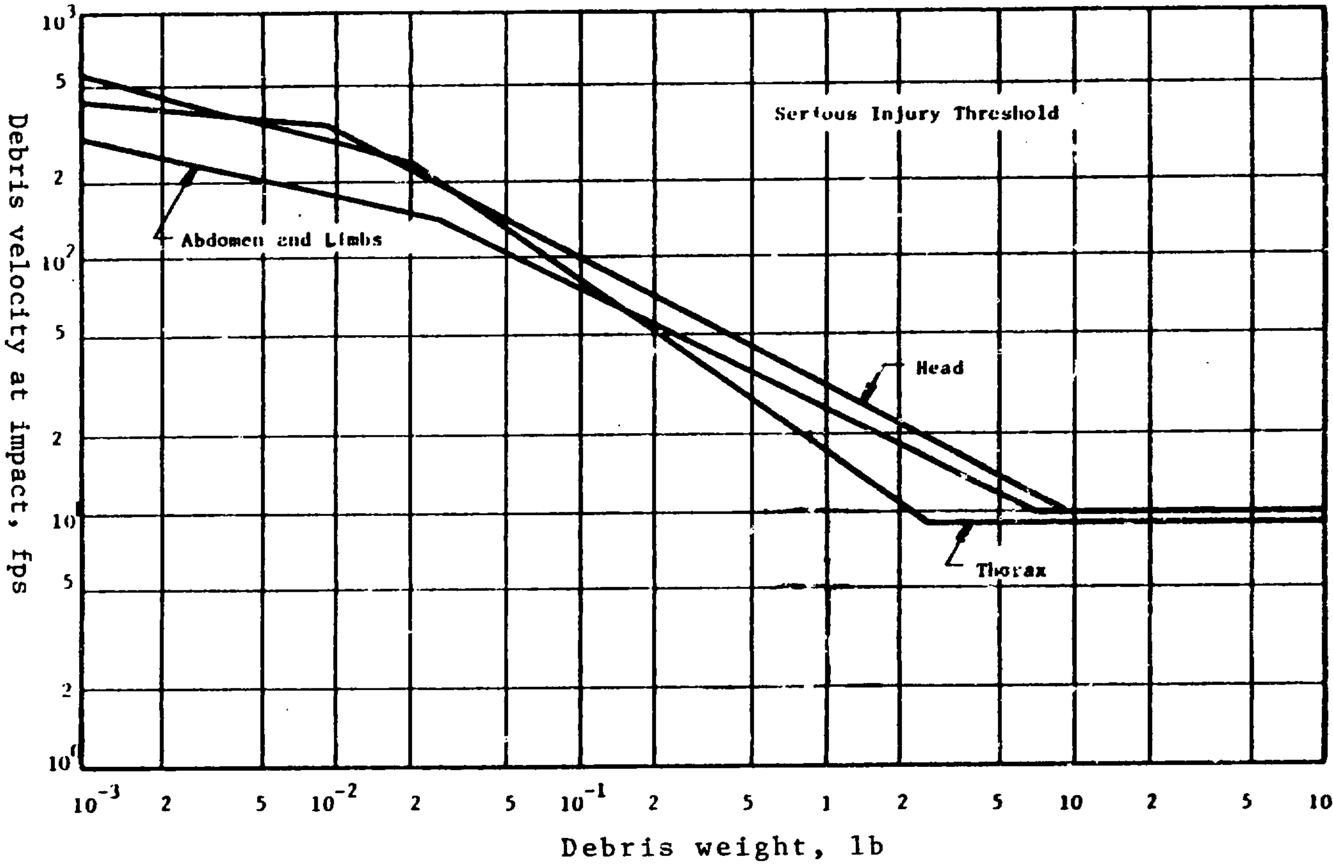


Figure 5-4. Personnel Response to Fragment Impact (Serious Injury Threshold) (reference 8)

Table 5-3. Free Fall Impact Velocities

ROOF HEIGHT	TIME (SEC)		VELOCITY (FT/SEC)	
	TO FLOOR	TO 5′-6" ABOVE FLR	TO FLOOR	TO 5′-6" ABOVE FLR
11	0.827	0.585	26.6	18.8
13	0.898	0.682	28.9	22.0
15	0.965	0.768	31.1	24.7
17	1.027	0.845	33.1	27.2
19	1.086	0.915	34.8	29.5
21	1.14	0.981	36.7	31.6

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DESKTOP COMPUTERS AND EXPLOSIVE SAFETY

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Introduction

The last ten years have witnessed a major evolution in computing capability. We started with programmable calculators and ended up with desk-top computers. This astounding change resulted from the capability to package many individual electronic components into a single chip. The capability of producing a single chip replacing thousands of equivalent "transistors" coupled with the ability to mass produce these chips at low cost has made it possible for every engineer to now have a computer at his desk which 10 years ago would have cost hundreds of thousands of dollars and filled a room. For example in 1980 the central processing unit chip (CPU) for a desk-top computer, an 8088 chip cost $350. Today the same chip costs $8. The memory of the desk-top computer largely has used the 4164 dynamic ram chip. The IBM PC uses a set of 9 of these chips for each book of 64k memory. The current cost of these chips is typical of mass-produced integrated circuits. Once the initial development costs are paid off and competition develops, prices decrease rapidly. To illustrate note the cost for 1 4164 chip:

1980	$175.00
1981	50.00
1982	15.00
1983	7.50
1984	5.00
1985	1.00

In 1980 512k of memory cost about $12,000; today it is under $100.

The U.S. computer industry once the sole producer of chips and computers has now found severe competition from Japan, Taiwan, and Korea. This competition has resulted in the U.S. losing not only the lead, but the total ability to compete in the dynamic-ram chip area. Japan developed the new 256k ram chip first. Now the major U.S. chip producers are abandoning that segment of the market. The major computer manufacturers like IBM are now faced with fully functioning "clones" being imported from Taiwan at 1/3 of the cost.

The engineer now can have at his desk a computer with 2 disk drives, 512k of memory and a monochrome monitor for $1,000.00. It is now possible to put the programs that were developed to run on main-frame computers on the desk-top computer.

FORTRAN Compilers

FORTRAN was developed by IBM in 1956 when computers were in the hands of scientists primarily dealing with algebraic formulas. The name FORTRAN (FORmula TRANslation) and the mathematical appearance of the language reflect the background of its designers. It remains the language of choice on today's super computers.

FORTRAN has been the computer language used by most engineers to develop programs. FORTRAN has been around about 30 years. Personal computer users can utilize FORTRAN; however, to do this a compiler must be used. A compiler is a program set which is used to translate the engineer's FORTRAN code to a usable machine language. The engineer can develop his FORTRAN code using any work processor when he has completed the development phase he "compiles" and "Links" the program. The compilation process uses a compiler program which checks each FORTRAN statement for errors and then creates an object program. The linking process uses a linking program to combine the object program and subprograms (subroutine) together with a library of standard functions (sine, cosine, etc.).

There are about 8 FORTRAN compilers for use on the personal computer. The main ones are:

IBM Professional
Microsoft MS FORTRAN
Lahey Computer Systems F77L
Ryan-McFarland
Supersoft FORTRAN-66

The first IBM/Microsoft FORTRAN compiler was released in 1982. It was slow, cumbersome and had limited capabilities. The situation has improved dramatically. IBM now markets a full implementation of FORTRAN-77 from Ryan-McFarland. Ryan-McFarland markets a similar version. Microsoft is a major producer of one of the most popular compilers. Their compiler uses a 2 pass system as opposed to the single pass system in the IBM/Ryan-Mcfarland compiler. This means you must run your FORTRAN source through 2 computer programs instead of one. A major advantage of the Microsoft compiler is that the use of the 8087 Math coprocessor chip is optional. It will support it if it is present and it will also work if it is not. This makes code more adaptable to a wider variety of computers. However the code runs slightly slower than the IBM/Ryan-Mcfarland compiled code. The Lahey compiler produces code which will run at speeds usually faster than Microsoft's code. Further the Lahey compiler is the fastest compiler taking half the time of IBM/Ryan-Mcfarland and Microsoft. Lahey requires an 8087 chip. The Supersoft FORTRAN-66 is an older version and as such would not support the FORTRAN-77 standard.

Each compiler has advantages and disadvantages in the size of code which can be compiled, the variation in FORTRAN language extensions and formats. One may check certain errors while another not. The IBM/Ryan-McFarland and Microsoft compilers operate on 192k and the Lahey compiler requires 256k.

PCBARCS

This section will illustrate the development of a computer program for the analysis of reinforced concrete slabs. Some years ago we were faced with the analysis of numerous blast resistant cells. The analysis was to follow the procedures outlined in TM 5-1300. The detailed procedures generally required about 40 man hours per cell per explosive location to analyze the response of each wall. To accomplish this task various portions of the analyses were automated and then combined into a single program. The program ran on a large main-frame computer. With the development and wide accessibility of desk top computers, we produced a version of BARCS which would work on a personal desk-top computer. The original program was a "batch" program designed to run from a set of data statement without user interaction. The program was redesigned to facilitate data input. Further the loads portion was separated from the response part to simplify usage. The program was made menu-driven and the user is guide through the input of the required data. When the TM5-1300 was revised the program was rewritten to include the updates. The 1986 version reflects the significant changes in loads computations and the revisions to the stiffness computation.

This section will explain the input data questions asked by the computer to calculate the blast loading on a wall. The basic geometry of the problem assumes that a spherical charge composed of TNT is located a distance away from the wall of interest and it is desired to calculate the average peak reflected pressure, the duration of this pressure and the impulse; additionally, the peak confined gas pressure, duration of the gas pressure and gas impulse may be computed from the cell geometry and vent area. The program assumes that the explosive is a sphere of TNT; no provision is made for explosive type or shape factors. The user must increase or decrease the actual explosive to account for the shape of the charge and/or the type of explosive. Additionally a safety factor may be applied to the explosive weight to increase it to account for unknowns. The program next asks for the distance the charge is away from the wall, the height of the wall, the length of the wall and the distance the explosive is to the left side of the wall, see Figure 1 for clarity. The program next asks for the cell volume for use in computing the gas pressure. The cell volume is the product of the height, width and length of the room containing the wall of interest. Also the area of the vent is required for the gas computation. This is the area of the frangible surface assumed to be blown away to provide venting of the gases after an explosion. The weight of the frangible material in pounds is required. The reflected impulse on the frangible panel is required. The program can include reflections from floor, roof and left and right side walls. Generally reflections from all these surfaces will occur and should be included. A reflection has been noted to occur from all surfaces even frangible surfaces.

This section will explain the input questions asked by the computer to calculate the response of a reinforced concrete slab to the shock and gas pressure pulse shown in Figure 2. The program asks the equivalent spherical TNT charge weight used to calculate the pressures, the peak average pressure acting over the wall, the duration of the shock pressure, the peak gas pressure, the duration of the gas pressure, and the total impulse. The units used for these variables are psi, msec, and psi-msec. The values are obtained directly from the output of the loads portion of the program. The program asks the wall height and width in feet. The program next asks for a code number to identify the boundary conditions of the wall giving the restraint fixity of the sides. Figure 3 shows the codes used. A code 1 has the base supported and all other sides free; a code 2 has the left side and floor fixed and the other two sides free; a code 3 has the roof free and the other sides fixed; a code 4 has all four sides fixed; a code 5 assumes oneway beam action with simply supported sides on two opposite sides and free sides the other way; a code 6 assumes oneway beam action as in 5 but with the two opposite sides fixed and the other two free; the code 7 assumes oneway beam action with one side simply supported and the other opposite side fixed and the two other sides free. The program asks for the allowable deflection limit in degrees. The usual range is between 2 and 12 degrees of support rotation depending on the degree of life safety required. A provision is included to compute a wall impulse capacity for use in composite concrete-sand fill walls.

The program next asks for the wall section and material properties, concrete thickness, ultimate dynamic concrete stress, dynamic yield stress of the reinforcing steel, lacing spacings if used. Units of inches and psi are used. The program gives the user a choice of how he may enter the reinforcing either in areas of steel per foot of wall or in standard U.S. bar sizes and bar spacings. Provision is made for horizontal and vertical reinforcement on the top (blast side) and bottom (opposite side).

OPTIMIZED DESIGN

The program PCBARCS has the capability to perform optimized design performing repeated iterations minimizing the cost of a concrete slab and adjusting the thickness of concrete and the amount of reinforcing steel. The optimization problem is complicated by the deflection limits and shear requirements which must be satisfied. The final selection depends upon the starting point. The iteration is performed a number of time until a limit is reached or the solution fails to change significantly. The user must verify the adequacy of the final design. It is possible that a solution could not be found which satisfies all constraints. Particularly the design of a reinforced concrete section without shear steel restricted to deflections less than 2 degrees is complicated by the fact that as flexural stiffness is increased to limit deflection additional shear strength is required which is based only on the unreinforced concrete section. Indeed there are combinations of load and geometry in which it is impossible to produce a section which meets all constraints without the use of shear reinforcement. This is one of the reasons the revised P397/TM5-1300 manual reduced the minimum requirements for flexural steel. When the optimized design section is selected the cost of concrete and steel is input.

The optimization problem consists of finding the least-cost structure that satisfies all the design constraints; or, stated in optimization terms:

Find X such that M(X) is a minimum and

$$g_i(X) \text{ LT } 0 \qquad i = 1,2,N$$

where X = vector of design variables

N = number of design constraints

g = vector of design constraints

M = objective function

Specifically for this problem, the design variables selected are areas of steel reinforcement and thickness of concrete. The design constraints are the flexural and shear limits. The objective function consists of the costs of formwork and concrete flexural and shear reinforcement.

Fixed Variables

explosive weight

wall height

wall length

height of explosive above floor

distance of explosive from left side of wall

distance of explosive from wall

reflection code

ultimate dynamic concrete strength

dynamic yield strength of reinforcing steel

rotation criterion

Design Parameters, X

$$X = \begin{array}{l} \text{concrete thickness} \\ \text{area of vertical reinforcing steel} \\ \text{area of horizontal reinforcing steel} \end{array}$$

Constraints, g (X)

maximum deflection

V(X) LT Vc for Theta LT 2 deg, maximum shear

Tc GT 10, minimum thickness

Asv GT 0.0015 bd, minimum vertical steel

Ash GT 0.0015 bd, minimum horizontal steel

The methodology selected uses the unconstrained minimization approach. The problem is converted to an unconstrained minimization by constructing a function. O, of the general form

$$O(X, r) = M(X) + P[g (X), \ldots, g (X), r]$$

For this problem the interior penalty function technique was selected. This methodology is suitable when gradients are not available, and, because the method uses the feasible region, a usable solution always results. The objective function is augmented with a penalty term that is small at points away from the constraints in the feasible region, but increases rapidly as the constraints are approached. The form is as follows:

$$O(X,r) = M(X) - r * \underset{j=1}{\overset{N}{\mathrm{SUM}}} \left(1 / (g_j (X)) \right)$$

where M is to be minimized over all X satisfyin g(X) Lt 0, j = 2...N. Note that if r is positive, then, since at any interior point all of the terms in the sum are negative, the effect is to add a positive penalty to M(X). As the boundary is approached, some g (X) will approach zero, and the penalty will increase rapidly. The parameter, r, will be made successively smaller in order to obtain the constrained minimum of M.

Objective Function, F

$$\text{Cost} = F = (H * L * TC)CC + (AV+AH)(L * H)CS + (AS)(L * H)CL$$

where
CC = Cost of concrete ($/cu ft)
CS = Cost of flexural reinforcement ($/cu in)
CL = Cost of shear reinforcement ($/cu in)
AS = Area shear reinforcement ($/cu in)

$$O = F + r * \sum_{j=1}^{N} \left(1 / \left(g_j (x) \right) \right)$$

where r is the penalty function.

The program requires a starting point in the feasible region before optimization can proceed This is accomplished automatically by the program by incrementing the design variables until a feasible point is reached. An algorithm which comprises the steps most commonly used is as follows:

1. Given a starting point Xo, satisfying all g(X) LT 0 and an initial value of r, minimize O to obtain Xmin.

2. Check for convergence of Xmin to the optimum.

3. If the convergence criterion is not satisfied, reduce r by c where c is less than 1.0

4. Compute a new starting point for the minimization, initialize the minimization algorithm, and repeat from step 1.

The minimization of O(x,r) is accomplished by a method developed by Powell using conjugate direction. Powell's method can be understood as follows: Given that the function has been minimized once in each of the coordinate directions and then in the associated pattern direction. Discard one of the coordinate directions in favor of the pattern direction for inclusion in the next minimizations, since this is likely to be a better direction than the discarded coordinate direction. After the next cycle of minimizations, generate a new pattern direction, and again replace one of the coordinate directions.

CAPABILITIES AND LIMITS OF THE PROGRAM

The program is written to follow the Department of Defense Triservice Manual TM5-1300 "Design of Structures To Resist the Effects of Accidental Explosions". The procedures used in the program are automated forms of the hand calculations performed in the manual and as such are no better or no worse. The methodology computes the approximate structural properties of a reinforced concrete slab and treats it as an equivalent single degree of freedom system solving for the dynamic response. This is a major simplification however experience has shown it to produce results which are adequate considering the errors in determining the loads. The results tend to be on the conservative side in favor of safe construction. This procedure is intended to give professional engineers a first cut in the design of complex slabs subject to dynamic blast loads.

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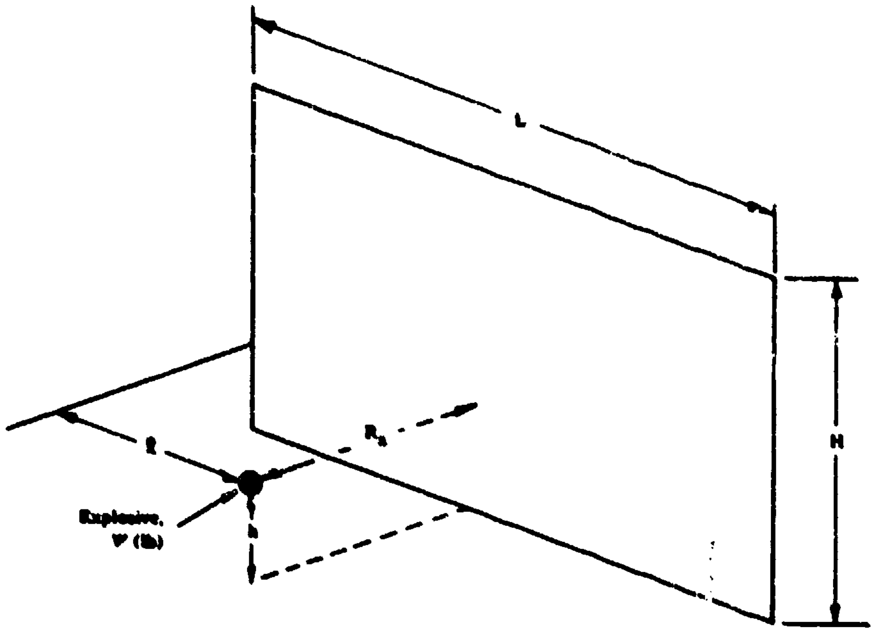

Figure 1. Wall geometry showing explosive.

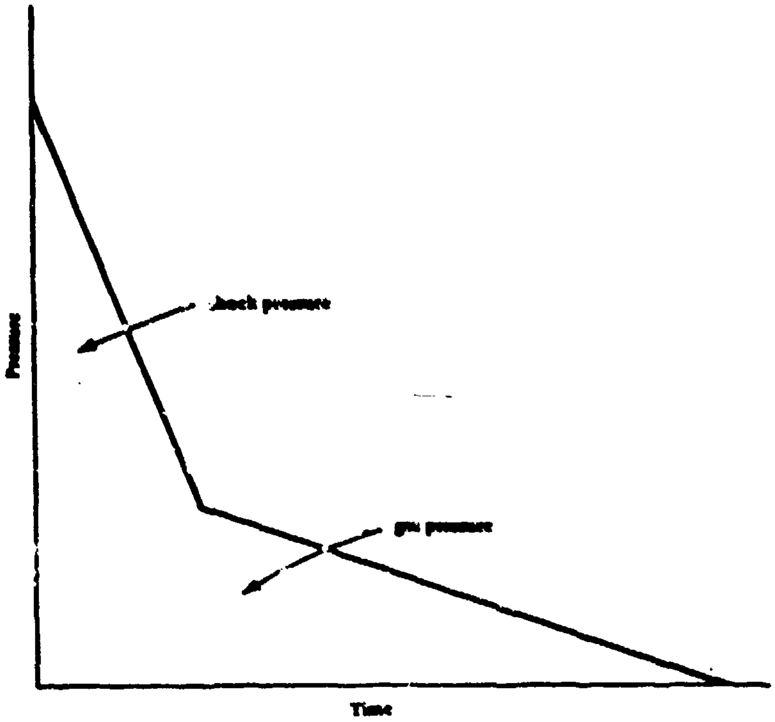

Figure 2. Equivalent pressure loading.

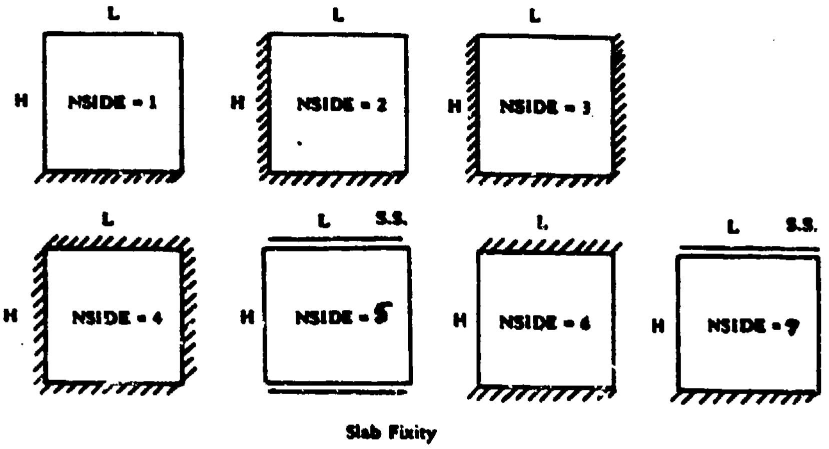

Figure 3. Wall geometry.

OPTIMAL DESIGN OF AMMUNITION STORAGE FACILITIES
TO
WITHSTAND CONVENTIONAL WEAPONS EFFECTS

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ABSTRACT

The paper deals with the optimal design of ammunition storage facilities to withstand conventional weapons attacks both in conventional warfare and in commando/terrorist attacks. The structures discussed are storage magazines and assembly facilities and represent actual projects already constructed. Several of the latest weapons and explosive devices used by terrorists worldwide are described, as well as potential damages to the ammunition related facilities and the surrounding structures and installations.

The conceptual security, hardening, and protection countermeasures are presented and the optimal design of the entire facility as well as of the individual structures is described.

Two computer codes developed in-house are shortly reviewed:

- The Computerized Security Analysis (CSA)
- The Computerized Hardening Analysis (CHA)

The use of these computer codes in the optimal design of ammunition related facilities to withstand conventional weapons effects is detailed.

INTRODUCTION

Lately, the threat of ammunition storage facilities being subjected to conventional weapons attacks from conventional warfare in regions where armed conflicts are occurring or could occur and from terrorist attacks worldwide has increased considerably.

Ammunition storage facilities are normally designed for the case of an accidental explosion occurring in one structure when the adjacent structures will not allow a sympathetic explosion to occur, it seems that designing these installations to withstand conventional weapons effects is not really required.

However, the following factors should be considered:

a. The much higher probability of a conventional weapons attack as compared to an accidental explosion.

b. The actual explosion effects to the surrounding facilities and to the people.

c. The costs of necessary repairs to the damaged installations.

d. The costs of the ammunition activated by the conventional weapons effects.

In light of the above considerations, recent designs of ammunition related facilities in many countries have incorporated requirements to withstand conventional weapons effects. In this paper, the subject of optimal design of these installations is addressed.

CONVENTIONAL WEAPONS ATTACKS

Conventional weapons attacks, as referred to in this paper, include:

- conventional warfare
- commando raids
- terrorist attacks

The weapons considered in the conventional warfare scenario are the normal ground, air, and sea delivered projectiles of all types usually containing different amounts of high-explosives.

The weapons associated with commando raids are the whole range of portable infantry weapons as well as weapons mounted on light vehicles. Relatively large quantities of explosives can also be considered for commando raids.

The weapons used in short-range terrorist attacks are similar to those for commando raids; additional weapons used by terrorists in long-range attacks should also be considered.

RECENT WEAPONS AND EXPLOSIVE DEVICES USED IN TERRORIST ATTACKS

Recently, several "new" types of weapons were used in long-range terrorist attacks broadening the range of weapons for which the designers must provide appropriate strength to the installations requiring protection.

Among these recent weapons one can find:

a. Anti-aircraft double-barrel guns mounted on light vehicles.

b. More powerfull RPG projectiles (Rocket-Propelled-Grenades).

c. Recoilless guns activated by two terrorists on the ground.

d. Different types of anti-tank military rockets.

e. Different types of ground-to-air rockets.

f. "Home-made" mortar launchers mounted on vehicles.

g. Different types of self-launching rocket-propelled projectiles.

h. Different types of rocket-launchers mounted on light vehicles.

In addition to the aforementioned weapons, several "new" types of attacks using explosive devices have occurred:

a. Throwing explosive devices over perimeter barrier systems by using slingshots.

b. Carrying explosive charges to the target by using remote-controlled small aircraft, gliders, balloons, etc.

c. Carrying explosive charges to the target by using remote-controlled small boats and mini-submarines.

In many recent instances, car-bombs and truck-bombs have been used against different installations worldwide with severe consequences; especially when the drivers commited suicide in performing the attack.

Finally, animals (mules, etc.) have also been used to carry explosives inside an installation and even innocent people inadvertently carrying explosives have been made to approach different targets.

In conclusion, we are witnessing both an increased number of terrorist attacks on military and civilian installations worldwide and also the use of more efficient and sophisticated weapons and explosive devices as well as the suicidal type of attacks.

AMMUNITION RELATED FACILITIES

The following ammunition related facilities could be considered as targets for conventional weapons attacks:

- Ammunition storage installations
    - open storage areas
    - barricaded structures
    - magazines
- Assembly facilities
- Manufacturing plants
- Testing facilities

As shown recently in several terrorist attacks in different countries, "soft targets" such as service facilities and even accommodation quarters were attacked.

POTENTIAL DAMAGES FROM CONVENTIONAL WEAPONS ATTACKS ON AMMUNITION RELATED FACILITIES

As we all know, ammunition related facilities are designed for the case of an accidental explosion; the risk of local damage is accepted while the requirement is to prevent sympathetic explosions in adjacent installations.

However, when considering conventional weapons attacks, the probability of the installations being hit and the inducing of an explosion is much higher than for the case of accidental explosion--for these types of attacks, the erplosion of more than one installation can easily be induced increasing the local damage considerably. Besides the much larger local damage which can be expected in conventional weapons attacks, higher levels of damage to the surroundings could be incurred with severe consequences to property and life.

For conventional weapons attacks, we should consider carefully the costs of repairing the damages to the installations as well as the time required to return to normal activity--especially in assembly and manufacturing facilities.

Finally, as the ammunition becomes more sophisticated and expensive, the actual costs of replacing damaged ammunition after an attack are being considered in different countries.

In conclusion, the consequences of conventional weapons attacks in general and a terrorist attack in particular can be quite severe and definitely much higher than for an accidental explosion.

DECISION ON STRENGTHENING AMMUNITION RELATED FACILITIES AGAINST CONVENTIONAL WEAPONS ATTACKS

Before deciding what action to take when considering conventional weapons attacks on ammunition related facilities, the following analysis should be performed:

a. A threat analysis in which all the possible types of attacks, weapons and explosive devices must be considered in a probabilistic way in direct connection with the specific installation.

b. A vulnerability analysis in which all the components of the installation must be considered and their vulnerability to the defined threats must be estimated.

c. A damage analysis in which the expected damages should be estimated in terms of damage to physical installations, damage to ammunition, disturbance to the facilities' normal functioning, and injuries to personnel and people outside the installation.

At this stage, the level of expected risk should be established and it should be concluded whether the expected risk is acceptable or not.

If the level of expected risk is acceptable, no further action will be taken. However, if the expected risk is unacceptable, strengthening of the facility against conventional weapons attacks is required.

COUNTERMEASURES TO REDUCE DAMAGES FROM CONVENTIONAL WEAPONS ATTACKS

The countermeasures to be applied against conventional weapons attacks are of the following types:

a. Active countermeasures--usually by human actions.

b. Passive countermeasures--usually by systems and physical measures.

c. Post-attack--emergency procedures.

Speaking as architects/engineers, our main contribution is in the field of passive countermeasures in the hardening of the installations but the implementation of all the other countermeasures should also be coordinated by the A/E design team.

OPTIMAL DESIGN OF THE FACILITY BY USING THE COMPUTERIZED SECURITY ANALYSIS (CSA)

In order to achieve an optimal design of the facility to withstand conventional weapons attacks, we have developed a Computerized Security Analysis (CSA) which is capable of the following:

a. The description of the facility as an input to the computer code.

b. The description of all types of attacks, weapons, and explosive devices as inputs to the computer code.

c. The description of all types of countermeasures as inputs to the computer codes.

d. The analysis of the combined effectiveness of the countermeasures against different threat scenarios.

e. The definition of the optimal combination of countermeasures which is most effective in countering a defined threat scenario.

f. The estimation of costs of the countermeasures and the calculation of the cost-effectiveness.

g. Repeating the above until reaching the optimal design of the facility.

The types of countermeasures considered in the CSA code are:

a. Preventive Countermeasures:

- general such as dispersal, redundant functions and systems,
- access control measures,
- anti-intrusion measures--intrusion detection and alarm systems, anti-intrusion barriers,
- hardening of structures,
- surveillance systems and personnel, and
- indirect measures such as shielding, camouflage, deceiving.

b. Response-to-the-Attack Measures:

- direct response of the security force, and
- help from outside organizations.

c. Post-Attack Measures:

- emergency measures such as fire fighting, quick repairs, medical aid.

The Computerized Security Analysis (CSA) code was applied to actual projects and has proved to be a useful tool which aided the designers in establishing an optimal, balanced set of countermeasures against conventional weapons attacks.

OPTIMAL DESIGN OF THE STRUCTURES BY USING THE COMPUTERIZED HARDENING ANALYSIS (CHA)

In order to achieve an optimal design for hardened structures to withstand conventional weapons attacks, we have developed a Computerized Hardening Analysis (CHA) which is capable of the following:

a. The description of the different structures as an input to the computer code.

b. The description of all types of attacks, weapons, and explosive devices as inputs to the computer code.

c. The description of architectural and structural hardening features for each structure.

d. The analysis of the weapons/explosive devices effects on the structures.

e. The estimation of the expected damages to the structures and their contents.

f. The estimation of the costs of the hardening measures.

g. The estimation of the cost-effectiveness of the hardening measures.

h. Repeating the above until reaching the optimal set of hardening measures.

The Computerized Hardening Analysis (CHA) code was applied to actual projects and has proven to be a useful tool which aided the designers in establishing an optimal, balanced set of architectural and structural hardening measures.

MAIN CHARACTERISTICS OF THE COMPUTERIZED SECURITY ANALYSIS (CSA) AND COMPUTERIZED HARDENING ANALYSIS (CHA) COMPUTER CODES

We would like to stress that the CSA and CHA computer codes are design tools and serve as help to the designers to achieve optimal cost-effective solutions.

The codes were developed by using first-hand knowledge on the latest weapons and explosive devices used in conventional weapons attacks.

The main characteristic of the CSA and CHA computer codes is that the analysis is not theoretical but is based on practical experience in the fields of weapons and explosive devices effects on actual structures, as well as the effectiveness of different security countermeasures to actual attacks.

Practical experience gained in the design and building of numerous hardened ammunition related facilities was also used in the CSA and CHA computer codes development. From a practical point of view, the CSA and CHA codes run on PC computer stations, are user-friendly, and provide outputs in formats enabling quick decision making.

The potential use of the CSA and CHA computer codes is as follows:

a. Optimal design of new installations.

b. Estimation of the effectiveness of the security/hardening/protection measures in existing installations.

c. Optimal design of additional strengthening measures for existing installations.

CONCLUSION

The practical experience gained in the last 18 years in designing and building hardened structures to withstand conventional weapons attacks was applied in the development of two computer codes serving as design tools--the Computerized Security Analysis (CSA) and the Computerized Hardening Analysis (CHA).

These proprietary computer codes have been applied to actual projects and have been proven as very helpful in the achievement of optimal designs.

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ACCIDENT-PRONE RISK-FACTORS
IN
THE PRODUCTION OF PYROTECHNIC AMMUNITIONS
AND
PREVENTIVE MEASURES THEREFOR

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ACCIDENT-PRONE RISK FACTORS
IN
THE PRODUCTION OF PYROTECHNIC AMMUNITIONS
AND
PREVENTIVE MEASURES THEREFOR

General.

1. After world war-II, pyrotechnics have become more of science than the medieval Art. 'Pyro-Technology' has become a specialised subject of study. The Pyrotechnic Industry has no longer remained an Empirical one.

1.1. The Pyrotechnic Ammunitions covered in this Paper are the conventional ones; and not the Pyro-devices currently extensively used in the Aero-Space Mission.

1.2. The scope of discussion in this paper has been restricted to the Manufacture of one of the main constituents of the Pyrotechnic Ammunition - The 'Candle'.

1.3. The Candle is compressed from the Pyrotechnic Compositions - either Bare with proper outer lining or encompassed into a metal container with suitable inner lining/coating. The size of the candle depends upon the calibre of the Ammunition.

1.4. In order that the Risk-factors and their severity are properly appreciated the various processing stages in the manufacture of the candle are shown in Table-1 - stage.I and Stage-II.

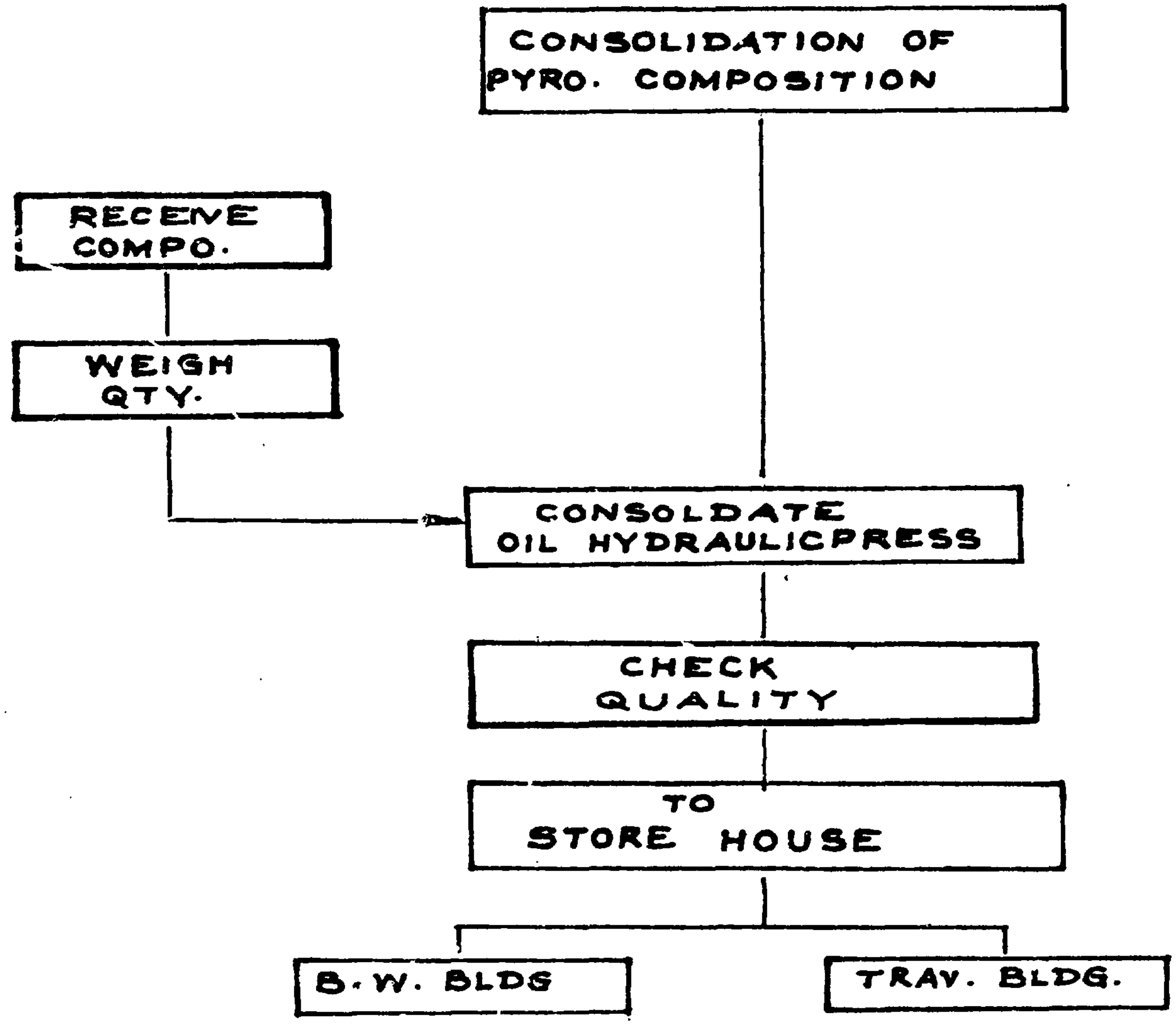
2.0. Manufacture of Candle.

The manufacture of the candle involves two major stages.

Stage.I. Manufacture of Pyrotechnic Composition.
Stage-II - Consolidation of the Composition to form the candle.

TABLE - I

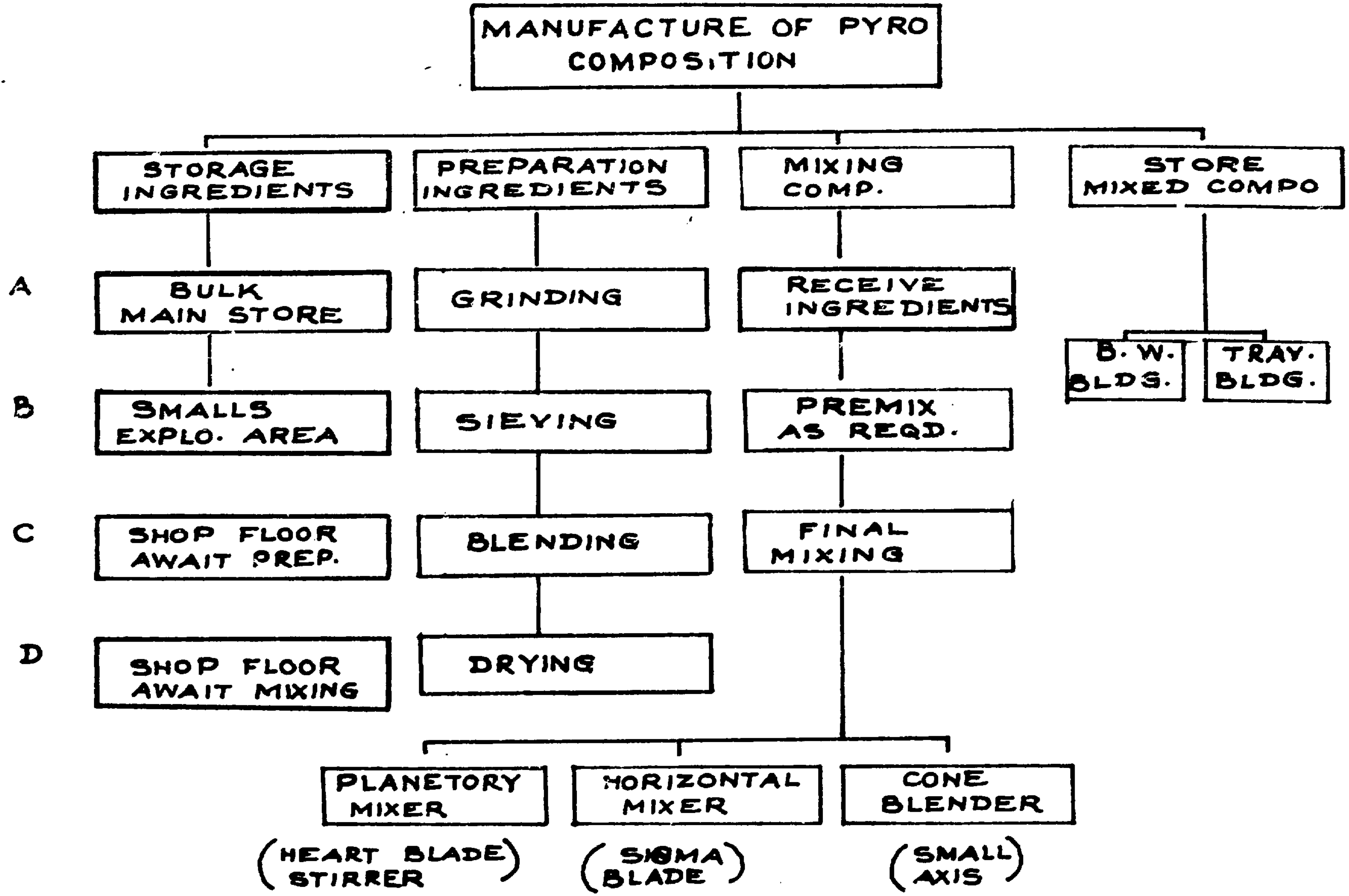
STAGE - II



MANUFACTURE OF CANDLE

STAGE - I

TABLE NO I



2.1. **Stage.I.**

The manufacture of Pyrotechnic composition comprises of the following steps:-

i) Storage of Ingredients.
ii) Preparation of Ingredients.
iii) Mixing of Ingredients to form the Pyrotechnic Composition.
iv) Interstage storage of the composition.

2.1.1. The major Ingredients used in the manufacture of the composition are:-

(1) Fuels	Magnesium Powder, Aluminium Powder, Boron, Zr.Nickel Alloy, Lactose, Starch.
(2) Binders.	Lithographic Varnish, Boiled Linseed Oil,Polyester Resin system.
(3) Oxidants	Nitrates of Sodium,potassium, Barium chromate, Potassium Chlorate, Potassium Perchlorate.
(4)Moderants	Calcium Oxalate, Magnesium Carbonate, Mannitol, Inert Liner-casting materials like DPG, MFD,Thiokol etc.
(5)Color Intensifiers.	Strontium Oxalate, Barium Chlorate, PVC Powder.

2.2. **Stage-II.**

The consolidation or the Pressing of the composition is normally carried out in Oil-Hydraulic Presses, although the recent trend is for Pneumatically operated Presses.

The Oil-Hydraulic Presases are erected inside the specially built cubicles whose three walls are R.C.C. and the rear wall is a brick-lined wall. There is an entrance door with a sight-window, Hatchway, control panel on the front wall.

The sequence of operation of these presses is so interlinked that unless the Hatchway door and the entrance door are fully closed, the Ram of the Press will not start operating. Similarly, after the pressing operation is over, the Hatchway will not open unless the Ram reaches its upper most position. If the Entrance door is kept open, the pressing operation will not start.

3.0. Accident-Prone Risk-Factors.

In any Industry, particularly the one in which large quantities of Hazardous materials are handled, it is just impossible to remove every risk factor.

Qualitatively, one can achieve the little more safety by providing more additive protective equipments. But then a stage is reached when one has to decide how far to go in removing such Risks. One has to initially identify the Risk-factors involved in everry process which are likely to lead accidents or 'Near-Misses', and attempt to minimise their probabilities.

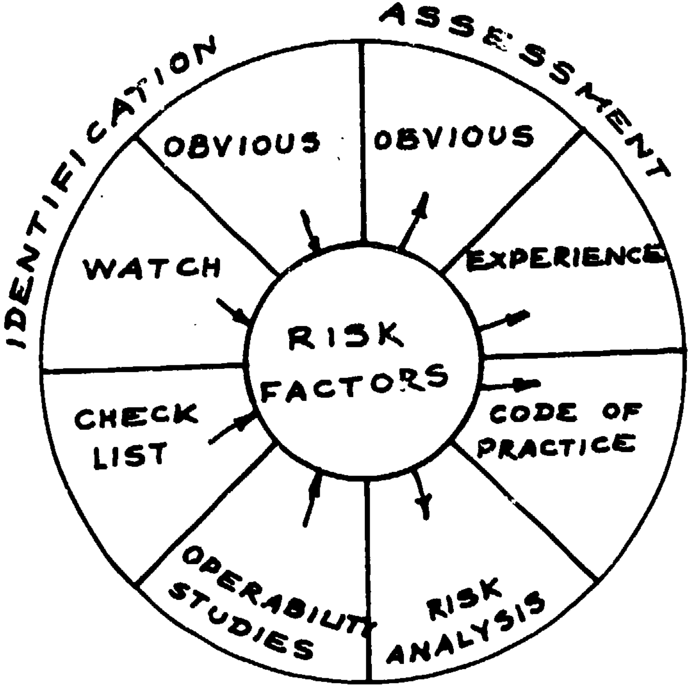


Figure - Methods of identifying and assessing Risk Factors.

One method of identifying Hazards or the Risk-Factors is the Hazard and Operability studies or 'Hazops'. The Technique is to search the proposed design systematically looking for every process detail and the integral part of the system in turn.

The step for identifying the problems is ___________ Possible causes - Process deviation - Possible consequences.

In order that all the possible causes are properly identified it is important to form a working Task Force consisting of members with wide spread of knowledge, expertise and adequate experience so that all the aspects of the study are fully covered. The search for the causes and the consequences of process deviation must be carried out thoroughly and systematically, looking for every eventuality and its likely effect. This becomes all the more important when the manufacture of the 'Pyro-candle' is to be studied.

3.1. The various Risk-Factors, after having carried out the study of the likely process deviations, can be grouped as under:-

i) Storage of Metallic Powders/Resins/Chemicals.
ii) Energy source.
iii) Release of materials.
iv) Process stage.
v) Fire and Explosion Risk.

These are discussed in the following paragraphs:-

3.1.1. **Storage.**

It will be seen from the Table-I that the various Ingredients are stored at three main places -
i) Main store (ii) Expense store inside the Explosive Area and (iii) at work place in the shop.

These storages and the movement of these materials pose Risk-factors especially when -

i) their correct nomenclatures along with their popular trade names are NOT properly indicated on the containers.

ii) their characteristics such as -

- Toxicity.
- Flammability.
- Incompatability with other chemicals.
- their Fire-Fighting Classification.
- the Protective Equipment to be used for their Handling.
- Special properties, if any.

are NOT clearly made known to those who directly handle these materials.

(iii) the special precautions for the disposal of spillages/rejected/deteriorated materials are NOT available to the shop operatives.

3.1.2. **Energy Source.**

In this particular study the finely divided metallic powders by themselves form the potential energy source.

(i) the Electrical - (a) an electric spark attaining temperature of thousands of degrees celsius, sufficient to ignite dust clouds, vapours.

(b) High intensity electrical discharges which can ignite solid materials.

(ii) Hot surfaces- (a) Electrical motors getting hot due to inadeqaute maintenance.

(b) the drives: which are likely to reach temperatures upto 250 degree centigrade and forming the risk factors to cause ignition/fire.

(iii) Friction and Impact sources -

The mechanical rubbing of one surface on another can cause ignition especially when hazardous materials get nipped between them - one of the major risk factor during pressing, which on many occasionsis a 'Near-miss' one.

The accidental fall of the tools on the sensitive materials/blended ingredients is another source to be taken note of. This can lead to explosion.

(iv) Self ignition source - Almost all the ingredients used in the manufacture of the candle are likely to ignite if heated sufficiently in air.

3.1.3. **Release of Materials.**

During the transference and the processing stages, spillages of finely divided metallic powders Unsaturated resins, the mixed compositions on the shop floor cannot be avoided. The do pose the potential Risk factors unless these are frequently swept not allowed to accumulate, and are solved in specified waste receptacles away from the working areas.

The toxic materials may also get inadvertantly released to increase the toxicity of the surrounding atmosphere beyond permissible limits. This may affect the Personnel working in that area and may lead to 'Near-misses' if not accidental situations.

3.1.4. **Process Stage.**

During the preparation of the Ingredients and the mixing operations all the ingredients/chemicals in the finely divided state are exposed in open containers in the working buildings.

These powders settle down in various places such as (i) the overhead A.C.Ductings (ii) the window sills (iii) the corners and sharp edges in the buildings (iv) the working tables and (v) the floorings. These fine floatingpowders would coalesce to form dust clouds. These, naturally, pose potential Risk-Factor.

If there are sudden changes in the temperature and humidity conditions e.g. the failure of Air-conditioning, the conditions in the working place would suddenly change - the temperatures would shoot up, the air may get too dry. Such changes are likely to be accidental in the summer of the Tropics.

During the pressing operations, if the pressure gauge on the presses did not record correct loads, the chances of excessive loads on the compositions cannot be ruled out. The compositions could get over heated and may blow'out'. The priming compositions which are normally more sensitive would add to such potential risk.

Most of the candles are now-a-days matured/cured in heating cup-boards. In such cases, there is likelihood that (i) there can be instrumentation failure controlling temperature and this can lead to overheating of the candles (ii) there are chances of the formation of local hot spots (probably due to improper un-uniform consolidation) which again can pose risks of spontaneous ignition, at times leading to explosion of the bulk candles.

3.1.5. Fire & Explosion Risk.

It would be natural to take the normal precautions of Fire fighting. However,in addition, the following have also to be taken care of, to avoid'near-miss' explosive situations:-

- Undue exposure of flammable materials to Dery atmospheres.
- Solar Radiation effect on sensitive chemicals/ mixed ingredients and/or compositions.
- Oily cotton waste/rags,left over wastes of Paints/ varnishes adjacent to the working buildings due to the release of Exothermic heat.

4.0. Preventive Measures.

Apex bodies of Experts comprising of members with wide spread of knowledge, long experience to their credit and expertise from the various specialised disciplines have carefully investigated the various Risk-factors and accidents and even the 'near misses' arising out of them over a period of more than three decades and have arrived at rationalised preventive measures for implementation.

These measures, of course, cannot be considered the panacea for all the situations; and it cannot be assured that the implementation of the proposed preventive measures would eliminate all the accidental situations and accidents will not take place.

4.1. The various preventive measures proposed can be grouped under the following major heads:-

i) Buildings and their construction.
ii) Working conditions in the storage areas.
iii) Working conditions in the process buildings.
iv) Preventive maintenance.
v) Safety of Personnel.

4.1.1. Buildings and their construction.

In addition to the normal norms for the safe and sturdy construction of the Buildings the following special factors have to be taken into consideration especially from the safety point of view:-

(i) Compile the assessment sheets for the storage of various ingredients.

(ii) Identify clearly the type of explosives/compositions to be handled/processed in the specified buildings.

(iii) Provide Blast wall protection or suitable traveses where necessary.

(iv)Provide a weak rear wall for the cubicles and even for the small bays where mixing, and/or pressing operations are carried out; and also to the Expense store houses.

(v) Provide conducting media/flooring to the Process Buildings and store houses.

(vi)Provide lightning arrestors on the buildings and personnel tester at the entrance of the buildings.

4.1.2.Storage conditions.

(i) Properly identify the various ingredients. Ensure that proper lables are affixed to their containers.

(ii) Take care to see that Incompatible ingredients are NOT stored at one and the same place. The details in this regard are fully made known to the operatives handling these.

(iii) Ensure that proper ventilations have been provided to these buildings; and also that adequate interspace is provided in between the stacks.

(iv) Ensure that the Temperature and humidity controls are implemented properly, periodically monitored and records for such checks maintained.

(v) Display prominently the classification of the contents in the storage buildings.

(vi) Provide proper fire fighting appliances in the vicinity of these buildings at the optimum distances; easily accessible to face emergencies.

(vii) Ensure that the unheading of the bulk packages is NOT carried out in the store houses/expenses stores. Provide a separate annexe (small room/cubicle) with proper protective measures forn this operation-

(viii) Ensure good housekeeping.

4.1.3. Working conditions in the Process Buildings.

A. Minimise dust accumulations:

- i) Provide sloping sills in the structures.
- ii) Keep the area of filters on the return air on the AC system to its optimum.
- iii) Provide dust extraction units at the operational points where the dust formation is inescapable.
- (iv) Maintain high dust velocities so as to avoid the settling of dusts.
- (v) Clean the AC ducts/the filters carefully and with specified frequencies.

B. Control Operating Conditions.

- i) Maintain optimum humidity conditions as per the process requirements.
- ii) Ensure that the dry-bulbs temperature inside the working place does not exceed 30 degree centigrade.
- iii) Avoid over-drying of the process area.
- iv) Where exothermic reactions are known to take place, spread out the compositions in trays in this layers for maturation to avoid hot spots.

v) From the safety aspect carry out most of the operations behind the shields and the barricades.

vi) Check up the machines for absence of static charge by testing with the static charge detector especially those where metallic powders/chemicals are ground and sieved.

vii) Do not pour bulk of the compositions sudenly into the hopper. There are chances of the development of static charge on the particles.

viii) Check up the condition of the tools - the moulds and the drifts for their close tolerances; for their physical condition and also for their life.

ix) Use brass hammers(and not steel hammers) for releasing the drifts which occasionally get jammed into the moulds.

C. Eliminate Ignition Sources.

i) Watch out for hot surfaces like Motors, Drives, heating coils and lights.

ii) Be alert to friction and impact sources especially (a) during the preparation of ingredients and (b) during the pressing operations.

iii) Avoid the nipping of the compositions.

iv) Ground all the metal containers, the flooring and even the Personnel to avoid the likelihood of generation of static charge.

D. Practice Good House-Keeping.

i) Ensure that the overhead AC ductings, the window sills are always kept clean.

ii) Remove the dust as often as possible. Use plain brooms to sweep off the dust.

iii) Keep the sloping surfaces in the structures clean.

iv) Keep the quantum of Toxic materials in the process building to the bare minimum.

v) Bring inside the pressing room quantities of explosives/ compositions sufficient for approx. 3 hours.

vi) Avoid accumulations of Oily waste, waste cotton, waste compositions/sweepings.

vii) Earmark specific areas for storage of such wastes sufficiently away from the bulk compositions.

viii) Arrange for the disposal of wastes as often as possible.

4.1.4. Preventive Maintenance.

It is important that all the machines, the equipments; the Instruments are properly periodically checked before any operation/processing stage is undertaken on them. This is essential so as to minimise the avoidable Risk factors and 'near-miss' accidental situations.

The following are some of the important points that need be checked:-

i) Rigidity of the couplings/joints.

ii) No leakages through the Pipe joints.

iii) Proper periodical greasing of the nipples and ensuring that they are not dry.

iv) Oil levels in the oil tanks of the power pack of the presses are proper - topped up when necessary.

v) Free rotation of the Drives manually without any abnormalities.

vi) Smooth and free movement of the Ram without jerks.

vii) Correct recordings on the pressure gauges against the statimeter readings.

viii) Smooth and normal functioning - fail-safe of the complete operational cycle on the press without any failure in the interlocks of the systems.

This is most important and should invariably be undertaken as a blank run before actual operations are carried out.

ix) The mixing machinery is checked for its cleanliness, free from foreign matters.

x) The Remote control system for these machines is free from defects.

5.0. **Safety of Personnel.**

The safety of the Personnel is by itself a subject which can be dealt as a specialised paper.

The paramount importance of the safety all the personnel either directly connected with the production activities or are the supporting personnel in the neighbourhood of the Explosive area needs no special emphasis.

5.1. **Responsibility of the Employer.**

(i) At the outset it is imperative on the part of the employer to provide the protective clothing and equipments suiting the particular operation to the operatives working on them.

(ii) The employer organises in his works the 'Safety Department' independent of other departments.

(iii) This Department formulates a comprehensive safety policy, and ensures that this Policy is implemented at all levels through out the organisation.

(iv) This department is headed by a 'Safety Manager' - directly reporting to the Top Executive - who is competent enough to interpret the various safety legislations; is able to advice on Safety matters to all the other departmental heads; is able to train the employees in implementing the preventive measures by persuasive methods impressing on them the consequences of not following these measures.

(v) This department does not only ensure that the existing safety systems and the incorporated built-in safety procedures are monitored but also carries out indepth study of these systems and prepare 'fail-safe' procedures in these system.

(vi) This department causes check on safety, preventive maintenance of plants and machinery and reports deficiencies observed directly to the Top Executive for his information and directing the corrective measures to the concerned departmental Heads.

(vii) The last but not the least important responsibility of the Employer is that he must discuss safety matters with the same importance as the Production and the productivity matters at every level. He encourages valuable suggestions in safety matters from the subordinates at all levels.

5.2. Responsibility of the Employee.

The employer, on his part, will ensure that all the statutory regulations, approved safety policy are fulfilled and the legal aspects well looked after.

It will be the primary responsibility of the employee to implement the preventive measures; to adopt all the safe practices; avoid any deviations from them, not only for one's own personal safety but the safety of his co-workers also.

He should ensure that -

(i) He is fully knowledgeable in regard to safety precautions to be followed by him for the operation he is undertaking and also is aware of the special dangers to be avoided.

(ii) He does not allow, either by himself or by others, any flame producing devices such as matches, lighters etc. in the sensitive areas.

(iii) None of them is under the influence of liquor or narcotics during the working hours at the work place.

(iv) He is fully alert to all the fire risk situations and takes prompt action during such emergent/dangerous situations to avoid service accidents.

5.2.1. It is pertinent to add that the employee, if he is alert, normally gets a first warning of the impending dangerous situations another if he is smart enough, properly trained, his prompt reflex actions in the first few minutes can, in most of the situations, play an important role in saving material losses as well as the injury to the personnel.

6.0. Case Studies.

There have been a few Accidents practically experienced during the past two decades and more, and quite a 'Near-miss situations. A few important of them are discussed here.

6.1. Unusual flash over from Electrical Circuit.

It had rained heavily in the forenoon of the particular day. The work was required to be suspended due to non-standard conditions of Temperature and Humidity in the working rooms. In the afternoon when the working conditions became satisfactory to start the work, the coating of Magnesium Powder with paraffin wax was to be commenced. In order to melt the wax the operator put the switch of the electrically heated table 'ON' when there was a sudden flash from the conduit.

The alert operator immediately put 'off' the switch and reported the incident to his superior.

When the situation was examined it was noticed that there was a minor crack developed from the wall-side of the conduit which had gone unnoticed; that there was a slight seepage of the rain water through this crack; that a very little portion of the sheath of the inside wire had become bare with the result that when the switch was put 'ON' the fine powder deposited on the conduit burnt with a white flash.

In order to avoid such conditions subsequently the use at the electrically heated table in the working area was suspended. The melting of wax was taken up in steam jacketted vessel, the wax in molten condition was brought for the necessary coating operation.

6.2. **Defective Tools.**

In one of the processing cubicles there was a loud 'bang' during the pressing of the composition. The ram was damaged, the mould broke into pieces. There was, however, no damage outside the cubicle to the ' Hatchway door and the entrance door.

On examination of the sets of tools in use for the pressing of this type of sensitive composition, it was noticed that these had been in use for much more than the specified pressings. Since the fresh sets of tools were not immediately available, and there was the exigency of work, the operators were using these old tools to complete their days target. Nothing had gone wrong with the use of these tools for nearly 200 pressings on the particular day before the incident.

It was recommended that the Works Inspection staff must check the tools everyday before the pressing operations are taken up,reject such of those which did not satisfy the quality parameter and must ensure that these are removed from the working area duly stamping the 'reject' stamps on them.

6.3. Use of wrong containers for compositions.

The 'interstage transport of the composition from the Expense store to the filling bay inside a container with a conical month was in vogue for quite a long period. Since nothing serious had taken place the use of such container was not seriously taken note of for replacement by other improved container.

On one fateful day, it happened that the composition freshly prepared and stored in this type of cobntainer(most likely not fully watered) was being transferred when there was some hissing sound from inside the container. This scared the operator. As the excessive heat had developed inside the container, the composition caught fire, and the operator dropped the container from his hand. This resulted in a loud bang and fatal injuries to the Operator.

On careful study it was realised that the conical shape had acted as a shell, burnt the container causing the explosion, shattering the container leading to the fatal injury.

The Court of Enquiry found fault -

(i) with the lack in monitoring system and (ii) with the use of these wrong type of container for such sensitive compositions.

6.4. UNdue delay in disposal.

One batch of mixed composition was noticed to have been wrongly mixed and rejected. The batch was immediately emptied into small containers and stored at a demarcated place away from the other compositions.

Due to oversight, this batch was left undisposed for a couple of days when one night shift there was a loud 'bang' from one of these containers which threw the adjacent containers helter-shelter. There was a slight damage to the window frame and partly to the adjacent door frame.

Even when this composition was taken to destructor ground for disposal and lighted, quite a few slivers were also thrown 'out'.

It was noted during the enquiry that the Operator, knowing that there was some mistake in the preparation of the batch had just emptied out the same without putting it for proper curing, with the result that there was formation of hot spots over a period which then caused spontaneous ignition of the contents leading to the 'bang' -In the case of other containers the composition had got hardened and hence some slivers at the destructor ground.

It was recommended that any batch of composition, once taken up for mixing, should be finished in the normal manner even if it is known not to have met the specified parameters and disposed without any undue delay.

7.0. CONCLUSION.

In conclusion, remember the following golden rules:-

(i) For the employer.

(a) Remember that 'safety' is not a factor that can be delegated.

(b) Conduct regular Training Programmes for the Supervisory Staff and the Skilled Craftsmen to impart the important characteristics of all the ingredients and safe working practices in handling the same.

(c) Conduct Fire fighting training programme and periodical fire practices to educate the employees to be alert to such situations.

(ii) For the employees.

(a) Do not under-estimate the Fire-risks accompanied with the processing of Pyrotechnic Ingredients and compositions.

(b) Be alert to dangerous situations likely to arise out ofn either the potential or actual hazard.

(c) Always handle Toxic materials and the mixed Compositions in small quantities to minimise the Risk-factors.

(d) Observe all the established safe practices laid down for the Processing, Handling, Storage and Disposal, keeping in mind the special precautions, and also special dangers to be avoided.

and last but not the least:

(e) Remember that 'Good House-keeping' is the key word for safe practices.

EXTREME HEAT PROTECTION FOR PYROTECHNIC HANDLERS OF Mg FLARES

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EXTREME HEAT PROTECTION
FOR
PYROTECHNIC HANDLERS OF Mg FLARES

Daniel R. Barrios, Dr. D. E. Davenport, Olen Nelson

1. INTRODUCTION

Because many stages in the production of infrared decoy flares (Mg/PTFE) require that the production workers operate close to many pounds of the flare material in both the granulated and pressed states, it is required that the workers wear fire suit type of protection at several stages of the process. Although the chemical reaction of an accidental ignition of this material does not generate large volumes of gas, so that blast is not a primary hazard, the heat of the reaction is above 4000°F and the afterburning of the excess magnesium vapor in air can generate plume temperatures of over 5000°.

This means that the major hazard is from the thermal radiation accompanying such high temperatures which is intense enough to ignite materials many feet away. Because the thermal pulse is relatively short (a few seconds), the hazard is quite different from that faced by the fireman or the steel mill worker for whom most suits were designed.

Furthermore, the worker has to perform many tasks where the stiffness, bulk and weight of the conventional fire suit make it very difficult for the worker to accomplish his task. If the exposure of a task requiring the use of a fire suit is relatively short, the worker may even be tempted to skip dressing properly in such a cumbersome outfit and thus subject himself to unnecessary hazard.

For all of these reasons, Tracor MBA and Star Glove and Safety Products Corporation set about looking at improved fire suit designs which were directed toward solving the pyrotechnic operator's safety problems. The pyrotechnic testing was carried out by Tracor MBA while the material design and samples were furnished by Olen Nelson of Star Glove.

Furthermore, since we had no quantitative data on how available suit materials performed in such an environment, we gathered samples from several present fire suit suppliers which could be subjected to a standard test to yield comparative data and guide our development tests.

2. The Test Environment

The first task was to select a test environment that simulated the type of hazard we were interested in and at a level at which we could gather data showing the relative performance of various materials.

We chose as a baseline a magnesium/PTFE (polytetrafluoroethylene) pellet mounted in an open, steel lined box, with the fire suit sample mounted at one open side at a distance of 12" from the flare pellet (See Figure 1).

The sample was a 6" x 8" rectangle of material held firmly between steel jaws in a holder mounted on a retractor bench. In the initial tests, some of the samples were withdrawn along the bench after a one-second exposure to simulate a worker retreating. It was found, however, that a stationary sample using a smaller pellet gave more reproducible results, so fixed samples were used in all of the later tests.

Two pellet sizes were tried, a 500 gram pellet and a 100 gram pellet each of which burned in 4 to 6 seconds. The plume from the larger pellet enveloped and destroyed many of the samples so completely that quantitative evaluation was difficult, so most of the the tests were carried out with the 100 gram pellets.

The initial tests were all carried out out-of-doors but, because even small breezes seem to cause the data to scatter, the final test series was carried out in a closed building with just an exhaust fan providing a controlled, gentle air movement to sweep away the smoke.

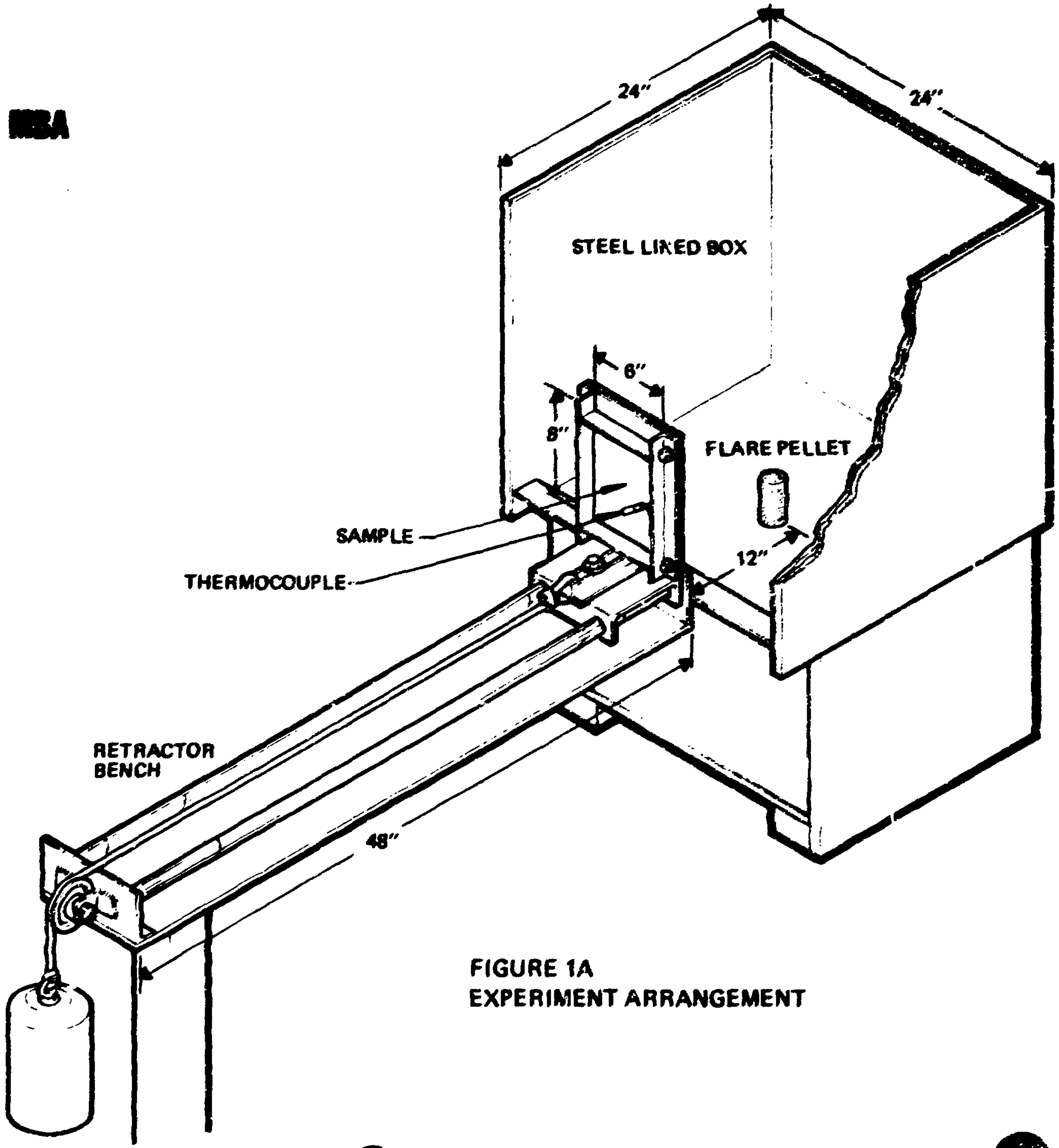
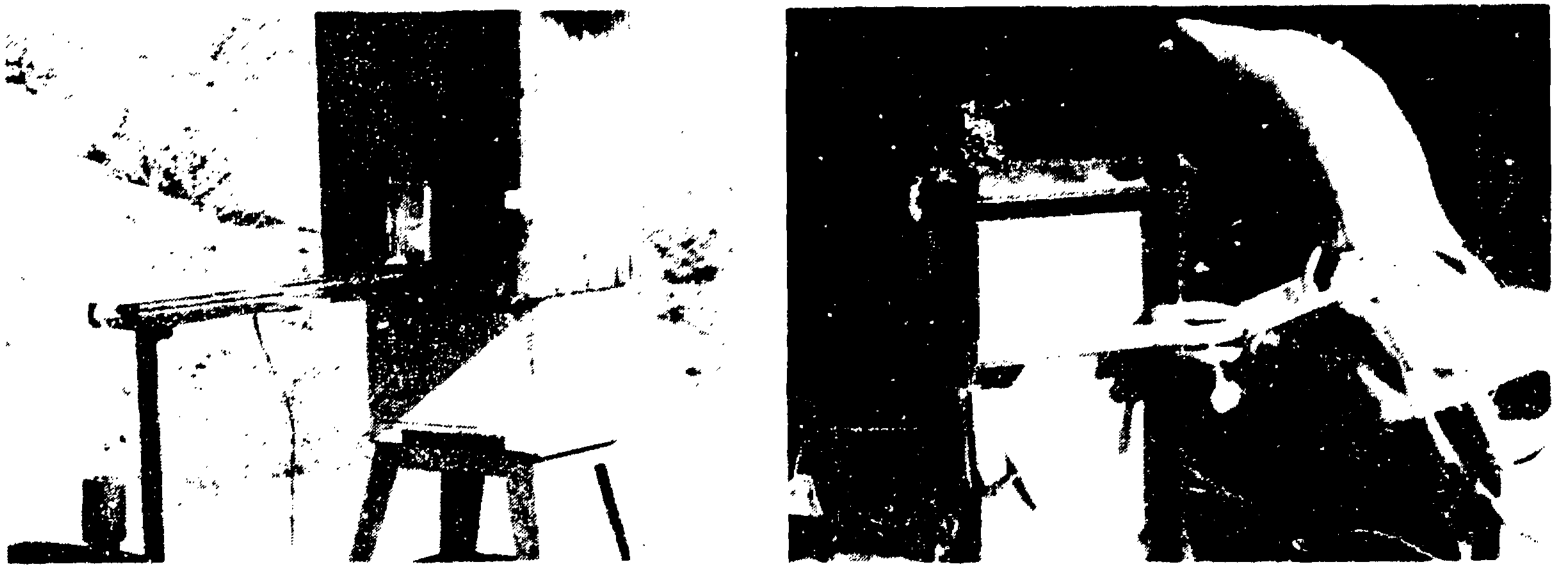


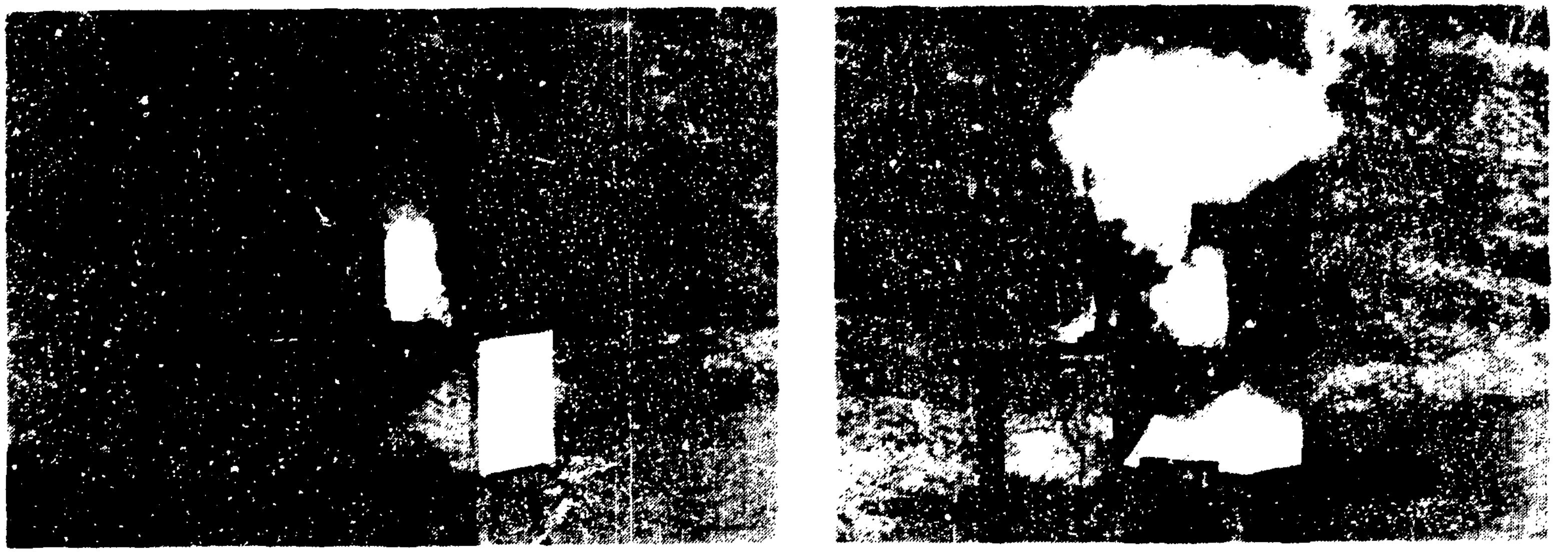
FIGURE 1A
EXPERIMENT ARRANGEMENT

Tracer MBA



1b. TEST SETUP

1c. SAMPLE HOLDER



1d. 100 GRAM TEST

1e. 500 GRAM TEST

FIGURE 1B

3. The Materials Tested

The available fire suit materials which were included in the test are shown in Table I.

4. Comparison of Test Environments

To obtain a comparison of the severity of the available test environments, a single type of fire suit sample (Encon's Pyrasteel) was run with all three environments:

100g pellet with fixed sample @ 12"
100g pellet with sample retracted after 1 sec
500g pellet with sample retracted after 1 sec

The data for these tests are shown in Figure 2.

The 100 gram pellet with the sample retracted after one second gave only a 35°F temperature rise while the 500 gram pellet with sample retraction gave about 250° temperature rise before the thermocouple detached from the sample. The fixed sample with the 100 gram pellet would appear to give some intermediate value but the thermocouple shorted out after about three seconds so a complete trace was not obtained.

Although this data is sketchy at best, when combined with the photos of Figure 1 which showed the extended fireball of the 500 gram flare, we concluded that the best basis for comparison would be the fixed sample with the 100 gram pellet. This would give a response which was great enough to make comparisons based on thermocouple response yet moderate enough not to completely destroy the sample.

TABLE I - FIRE SUIT TEST MATERIALS

Pyrasteel	Encon	9.7 oz/yd^2	Al Coated Fabric	
P-29 Panotex	Encon	9.4 oz/yd^2	Black Coated Fabric	Withstand 1650^{o}F for 3 - 5 min, 170 w/cm^2 for 2 sec
Protex III Felt	Encon	18.3 oz/yd^2	Black Coated Felt	Withstand 1650^{o}F for 10 min - designed as an insul. liner for Pyrasteel material
Fyrepel #1	Fyrepel		Al Coated Fiberglass w/Nomex felt backing	
Fyrepel #2	Fyrepel		Al Coated Kevlar/Fiberglass w/Nomex felt backing	
Fyrepel #3	Fyrepel		Al Coated PBI*/Kevlar w/Nomex felt backing	
PBI Knit	Star Glove	9½ oz/yd^2	50% PBI plus 50% permanent flame retardant rayon (PFR rayon)	
Aluminized PBI Knit	Star Glove	12 oz/yd^2		
Aluminized Kevlar Knit	Star Glove	6 oz/yd^2	Blend of PBI, PFR rayon and Kevlar	
PBI Glass Felt	Star Glove	12 oz/yd^2	3/16" thick 50/50 blend of PBI and β glass	

* Polybenzimidazole

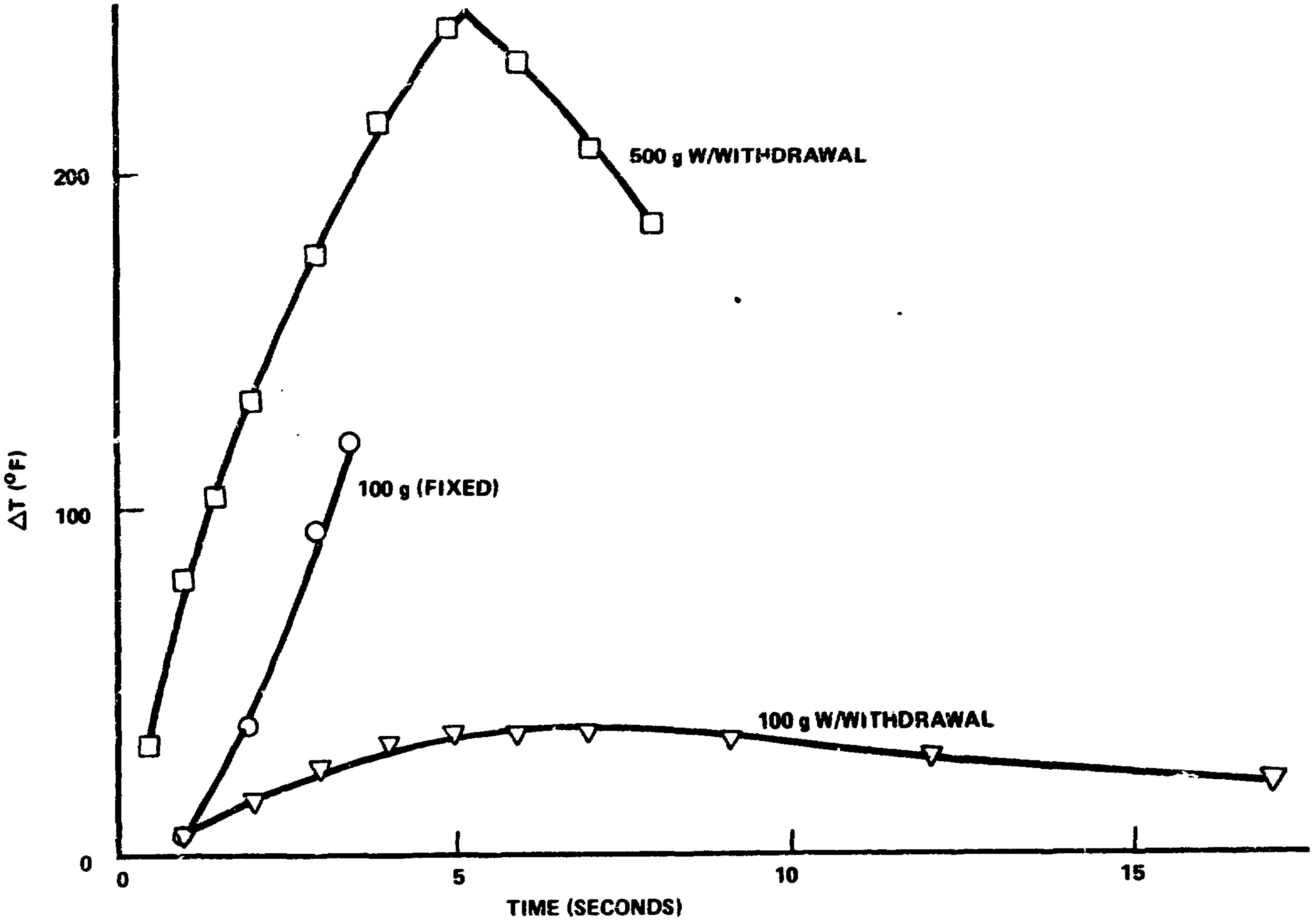


FIGURE 2
COMPARISON OF ENVIRONMENTS

5. First Test Series

A. 500 Gram Tests

Additional tests were carried out with the 500 gram pellets (with sample removal after one second) just for information and they are given in Figure 3. The samples used were the Encon which had no felt backing, the Protex III which is designed as a backing felt, and three aluminum coated fabrics which had felt backings.

These tests confirm that with a felt backing, this scenario gives fairly modest peak temperatures, but because of the variability in the shape of the plume produced by the mild breezes, the quantitative results were regarded as suspect. In the case of the two Fyrepel fabrics, the aluminum coatings were not even scorched which indicated that the plume did not expand as rapidly toward the sample as in the other cases. This again indicates that this scenario is too non-reproducible to use for sample comparison or evaluation.

B. 100 Gram Tests

Figure 4 shows the results of the tests with the fixed sample with the 100 gram pellets. Again the samples without felt backing showed very rapid temperature rises, whereas the samples with a felt backing showed quite tolerable temperature rises with the Fyrepel materials being best. Since neither the Protex III or Star Glove material were aluminum coated, the tests suggest the importance of an aluminum coating in reducing the radiation input when dealing with such high temperature inputs. In the Fyrepel 2 test, the movies indicate that the 100 gram pellet came loose and moved toward the sample in the middle of the burn. This probably accounts for its relatively high temperature compared to the values seen with the other two Fyrepel fabrics.

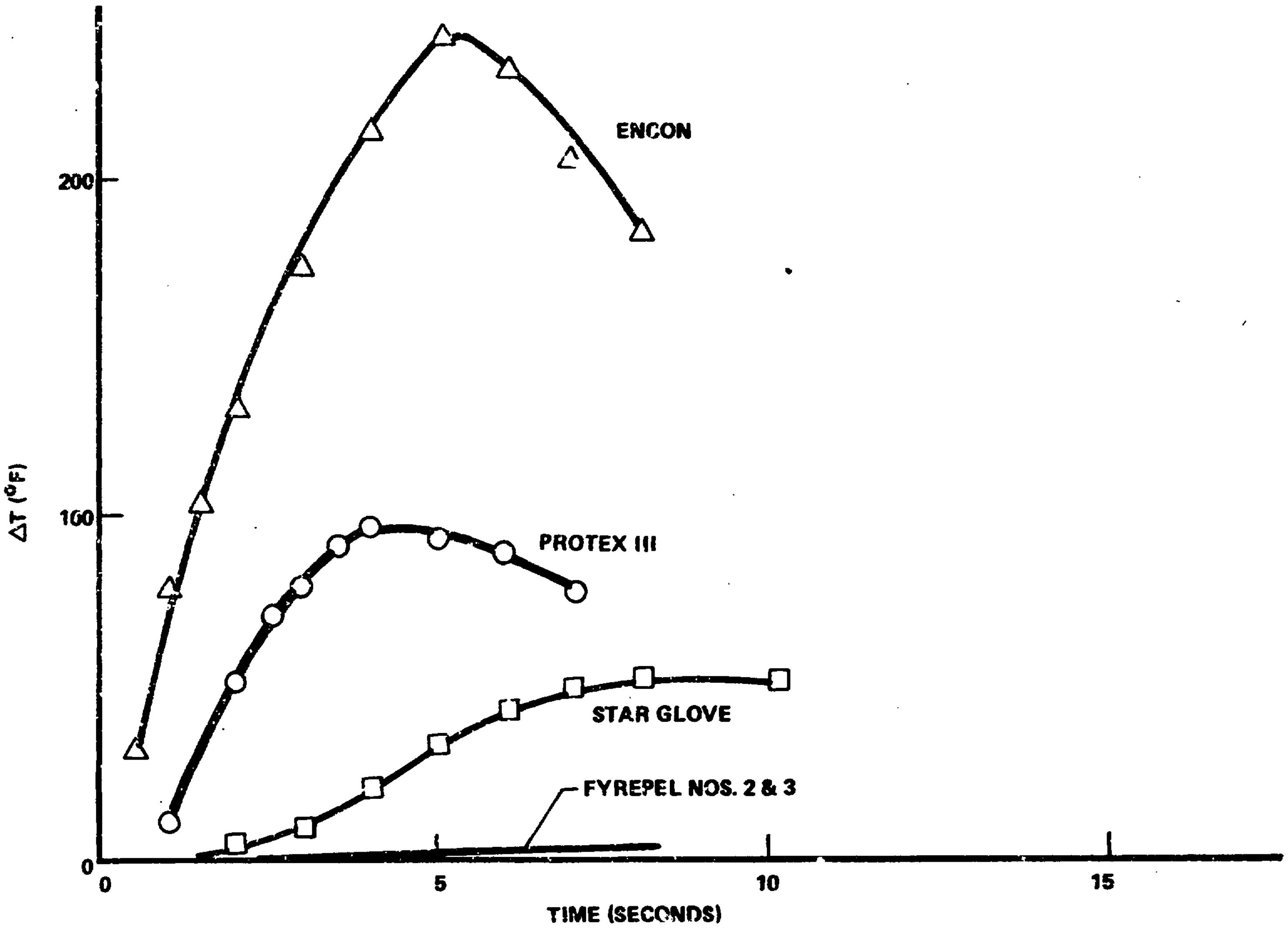


FIGURE 3
500 GRAM PELLET W/WITHDRAWAL OF SAMPLE

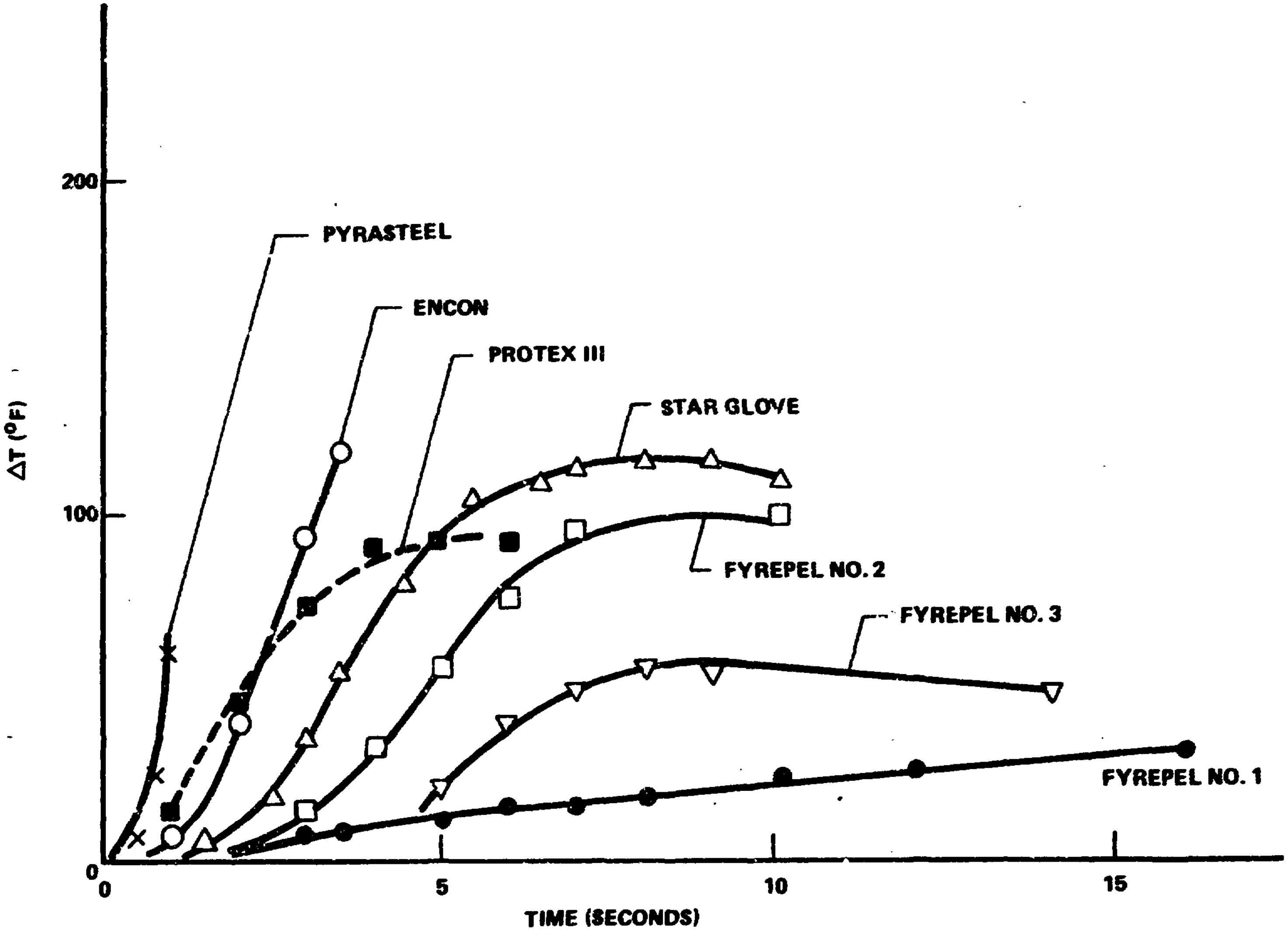


FIGURE 4
100 GRAM PELLET WITH FIXED SAMPLE AT 12 INCHES

5. Importance of Aluminized Coating - Second Test Series

In order to gather further information on the importance of the aluminized coating for this scenario in which the fabric is not directly in the flame, we looked at further combinations. Since we were interested in as light and comfortable a suit as possible, we used the PBI material in both knit and felt forms. The results are shown in Figure 5.

If one compares the results of using only the lightweight PBI knit material, with and without the aluminized coating, it is seen that both give very fast temperature rises which reach unacceptable temperature levels.

When one backs the aluminized knit with another knit layer, the temperature rise becomes much slower and reaches tolerable levels. When the aluminized knit is backed by the PBI felt, the temperature rise is almost trivial and compares favorably with the best of the Fyrepel results obtained previously.

In this test we also exposed one of the Star Glove gloves which has no aluminized coating but does have the PBI felt backing. In this case the thermocouple was mounted inside the glove in the palm which was located about where the other samples were mounted. The temperature rise can be compared to that obtained with the aluminized knit with the felt backing and one sees the significantly greater temperature rise one gets without the aluminum coating. The glove results are comparable to those one gets when backing an aluminized knit with only a knit.

When these results are compared with the previous Star Glove data with non-aluminized materials, one can see the importance of an aluminized coating, when the hazard is largely a radiative source.

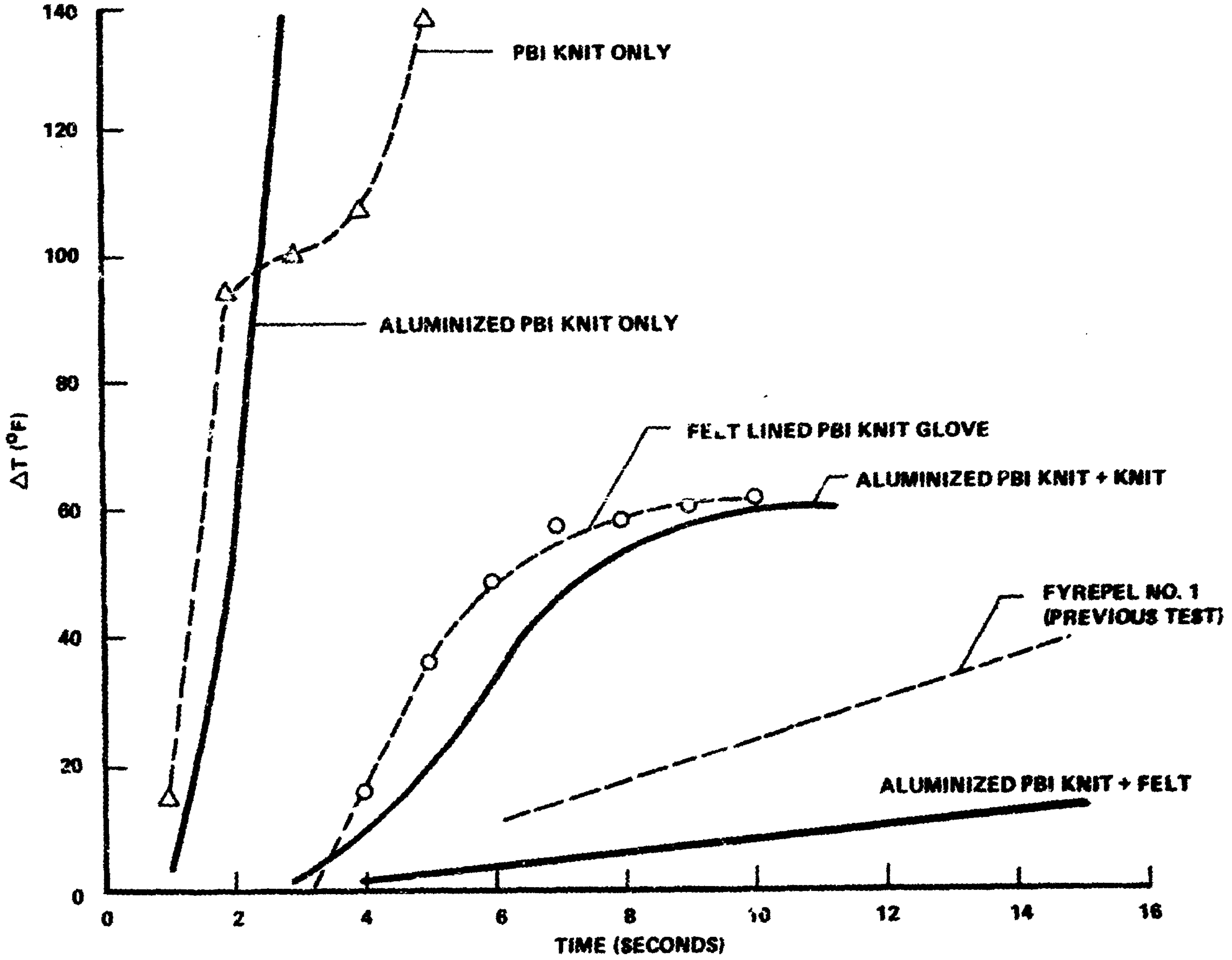


FIGURE 5
TESTS OF ALUMINIZED KNIT EFFECTIVENESS

6. Optimizing the Design

At this stage we felt we had a qualitative feel for the performance parameters and needed to get more quantitative data in order to select an optimum design. The test setup was moved indoors in order to obtain better reproducibility. The important design parameters considered for optimization were a) protection, b) comfort, and c) cost. The PBI seemed to give the best protection and comfort but was the most expensive of the materials. Therefore it was decided to test various felts with the aluminized PBI knit to establish the level of protection that could be achieved.

Figure 6 shows the results using PBI, fiberglass and Kevlar felts behind the aluminized PBI knit. Note in this case the actual temperatures are plotted instead of the temperature increases. Although the data is not complete since the thermocouples detached from the fabrics about 200°F, it is seen PBI is clearly best with Kevlar knit second and fiberglass probably not acceptable.

In the fourth case we attempted to use an aluminized Kevlar knit as the protection for the fiberglass felt and found that the Kevlar burned from the intense radiation and gave temperatures of about 300°F. This indicates the intense nature of the radiation field and why materials such as PBI are useful in this application.

At this stage of the test it was suggested that we consider a second aluminized layer in case the heat transfer from the front aluminized knit layer to the second layer was predominantly radiation since contact between the layers was random at best. The results are shown in Figure 7.

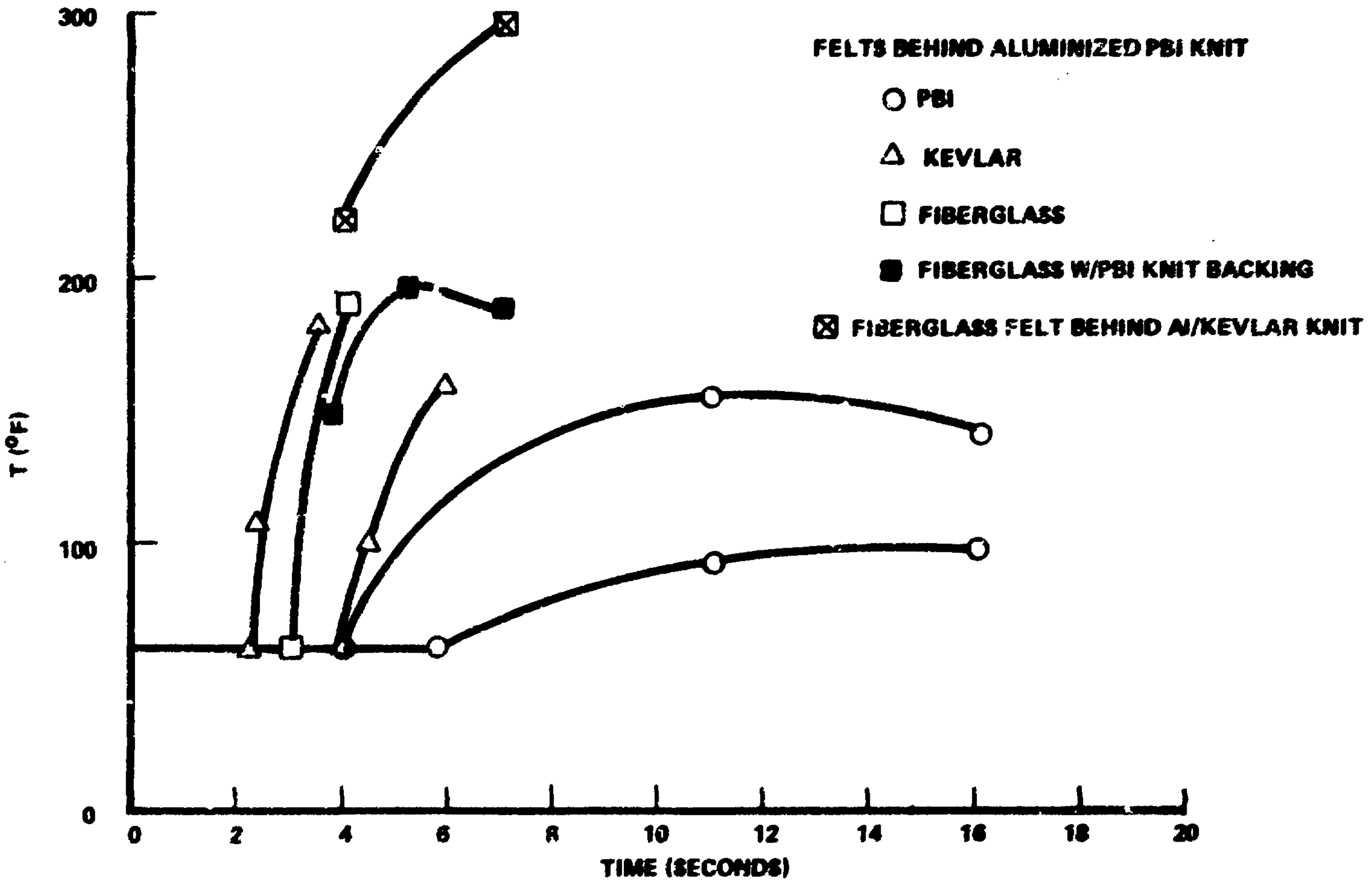


FIGURE 6
COMPARISON OF VARIOUS FELTS

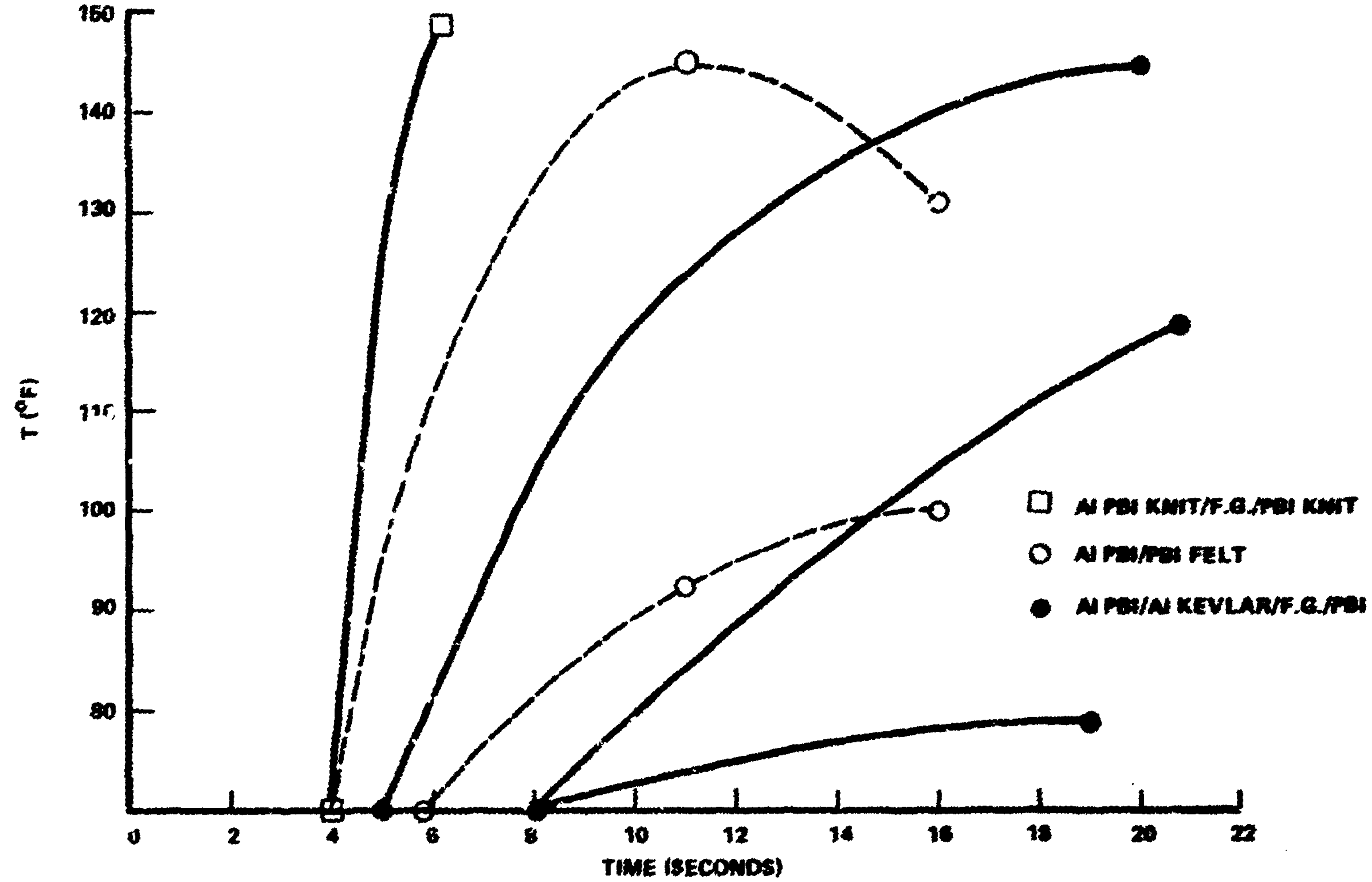


FIGURE 7
EFFECT OF SECOND ALUMINIZED LAYER

The temperature scale in this graph has been expanded to make it easier to read the results. A single aluminized layer over fiberglass with a knit backing was rerun for comparison and appears as the steepest curve rising above 200°F. (Note again these are measured temperatures with a base temperature of 60°F.) The two curves for a single aluminized PBI knit in front of PBI felt were transferred from the previous curve for comparison. Then three samples were run with an aluminized PBI knit backed by an aluminized Kevlar knit, a fiberglass felt, and a final PBI knit for comfort.

Although the reproducibility leaves something to be desired, it is clear that this four-layer sandwich compares favorably with the pure PBI material. In this case the aluminized Kevlar as a second layer was able to withstand the temperature and served well as an isolation barrier. It delayed the start of the temperature rise by 2 to 4 seconds and cut the peak temperature down to a very modest level.

7. Fabric Test Conclusions

The PBI materials provide an excellent resistance to temperature so are ideal for the backing for an aluminum coating layer. Because they are comfortable, the PBI's knits form an excellent liner material for a fire suit. If one inserts a second aluminized layer in front of the felt to reduce radiation transfer, one may use the low cost fiberglass felts and still obtain excellent fire protection.

8. Fire Suit Design

The fire suit construction was designed to protect the wearer against the accidental ignition of 50 - 100 pounds of magnesium/Teflon flare granules contained in a pot on a low table or cart.

The criteria for construction were taken from two major areas - the protection that the suit would offer against this thermal load and the usability of the suit by a wearer in the work environment. Only a proper melding of these sometimes conflicting requirements can an acceptable suit be designed.

The previous tests had shown that the PBI based hybrid fabrics could provide the thermal stability usually found only in the much heavier glass fabrics and with a great deal more comfort and flexibility. This stability is provided by the high decomposition temperature of the PBI material and the fact that it slowly carbonizes under excess thermal load maintaining its fibrous nature.

The PBI also has a remarkable moisture absorbance capability (50% greater than cotton) which makes it a very comfortable static-free fabric against the skin even when blended with 50% PFR rayon.

The four layer protective design tested in the previous experiments used knit fabrics in front of and behind the felts since they offer a great deal more flexibility than woven fabrics and would make it much easier for the wearer to perform his necessary tasks. At the same time, the knit fabrics provide over 50% more air space in the fabric than a woven material so one gains additional insulation without additional weight.

Finally, the four layer design provides both the two aluminized layers and the three air interfaces which are very effective insulators with a minimum of added weight.

The suit construction itself provides for improved user comfort in several ways. The new hood design provides the user with a large 8" x 14" gold coated window for excellent downward visibility as well as peripheral with a hood weight reduction of 25%. The visor gives minimum distortion and is coated to provide anti-fogging protection. Hood vents designed for the pyrotechnic type exposure aid in wearer comfort without sacrificing safety.

The storm flap design on the front of the suit provides an easy protection for any possible exposed area of the chest, while the hood and shoulder drape provide additional seals at joints. An internal spandex system at coat bottom provides a seal at this juncture, but allowing full freedom and movement. The sleeves and cuffs have an internal double knit thumb type wristlet and anklet to provide seals in this areas.

Gloves are gauntlet type and include the layered concept for protection. Dexterity is the prime concern here and the gloves are capable of handling the small parts and functions necessary for this type of job.

The coat is designed without a collar to reduce weight. The necessity of a collar was not evident. The coat pattern is also a special design for shoulder and arm freedom. Properly sized garments have no restriction in total movement of all parts of the body.

Integral spats were designed for the shoes to allow for the special conductive shoes worn. The general suit design has a continuous outershell of the aluminized STAR/PBI knit fabric. The inner liner concept is positioned on the front half of the total garment structure only, with the sleeves fully insulated.

The final suit designed for the test is shown in Figure 8. The hood assembly weighs about 5 pounds while the rest of the assembly weighs only 11-1/4 pounds. The suit would retail for about $1500.00.

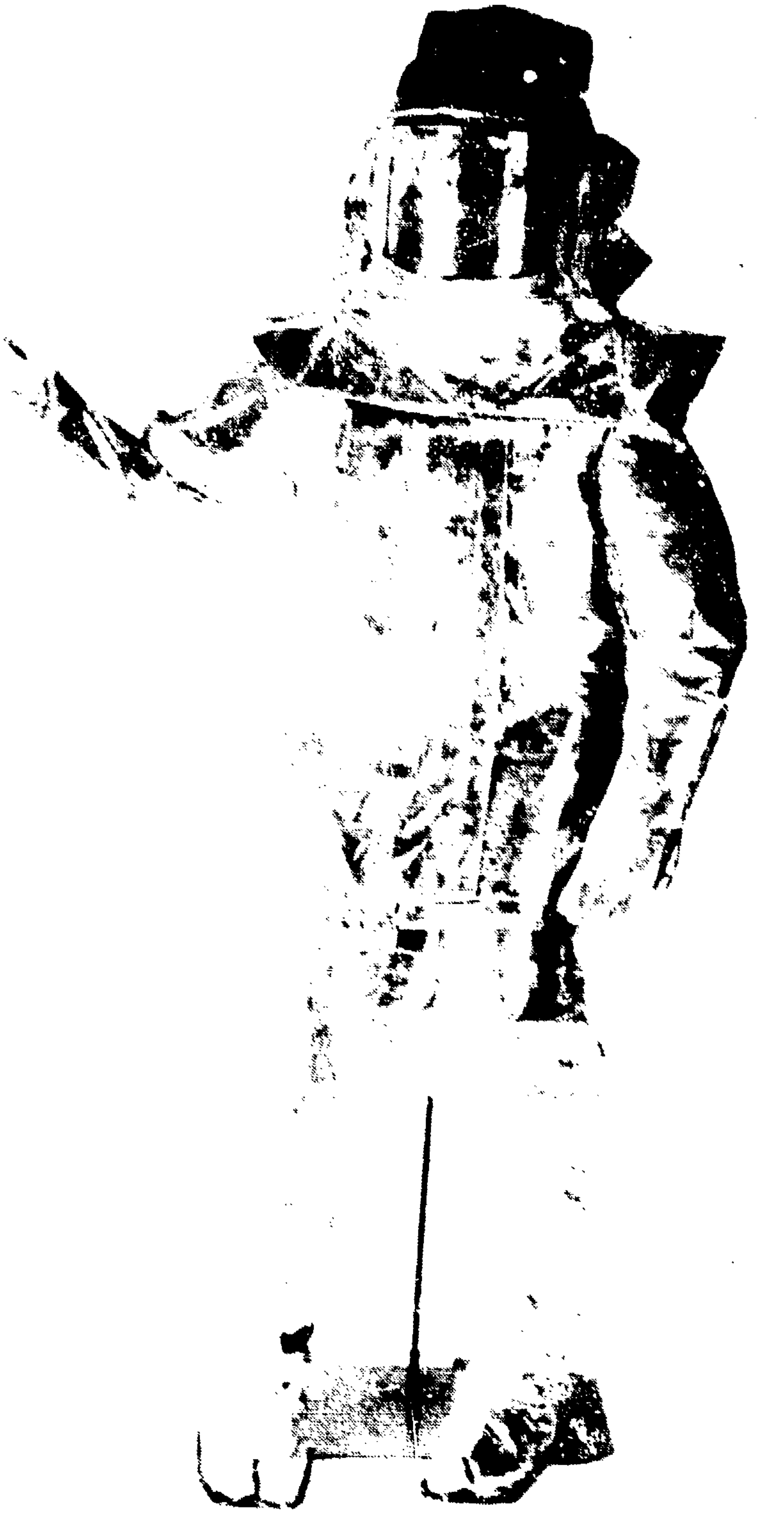


FIGURE 8
FIRE SUIT DESIGN

9. Fire Suit Test

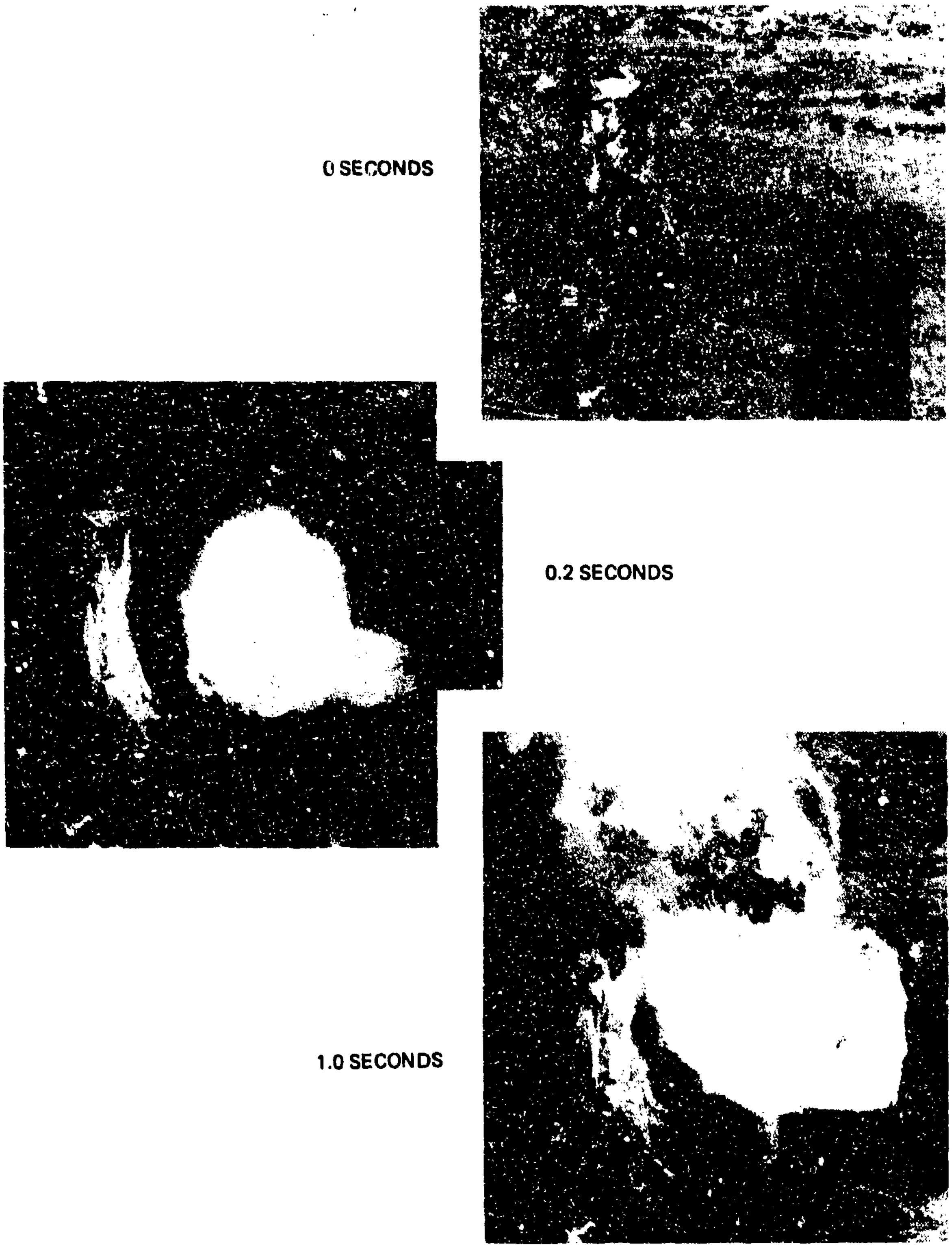
To test the complete suit against a possible accidental ignition, it was instrumented with thermocouples, placed on a dummy mounted at 3 feet from a barrel with 37 pounds of granulated Mg/PTFE blend (See Figure 9).

Thermocouples were attached to the inside surface of the suit for the leg, body, arm and hand, and to the dummy surface for the lip and ear locations. The lip location was chosen as an area looking directly through the gold-coated face shield so it would show direct response to the radiation, while the ear location was directly opposite a helmet vent and would see mostly the hot air entering through the vent.

The thermocouple responses from the test are shown in Figure 10. The lip and ear thermocouples responded the quickest and gave the highest readings which were only 20 - 30°F above ambient. All of the other thermocouples showed very slow rises to only 10 - 15° above ambient.

The development and size of the plume are shown in Figure 9. It is seen that the plume grows in size as it rises and the excess magnesium vapor is oxidized in the air. This is graphically indicated by the scorched areas on the suit being largely limited to the face shield and upper portions of the helmet (Figure 8).

These results also indicate the importance of using a high ceiling room for pyrotechnic operations so that the plume can rise rapidly away from the worker and reduce the radiation exposure. Since radiation intensity falls off nearly as the cube of the distance, it doesn't take much distance to make a radical reduction in the intensity. This is seen in the difference in the scorch obtained on the helmet compared to very little discoloration seen on the hand which was also facing upward.



0 SECONDS

0.2 SECONDS

1.0 SECONDS

FIGURE 9
FIRESUIT TEST

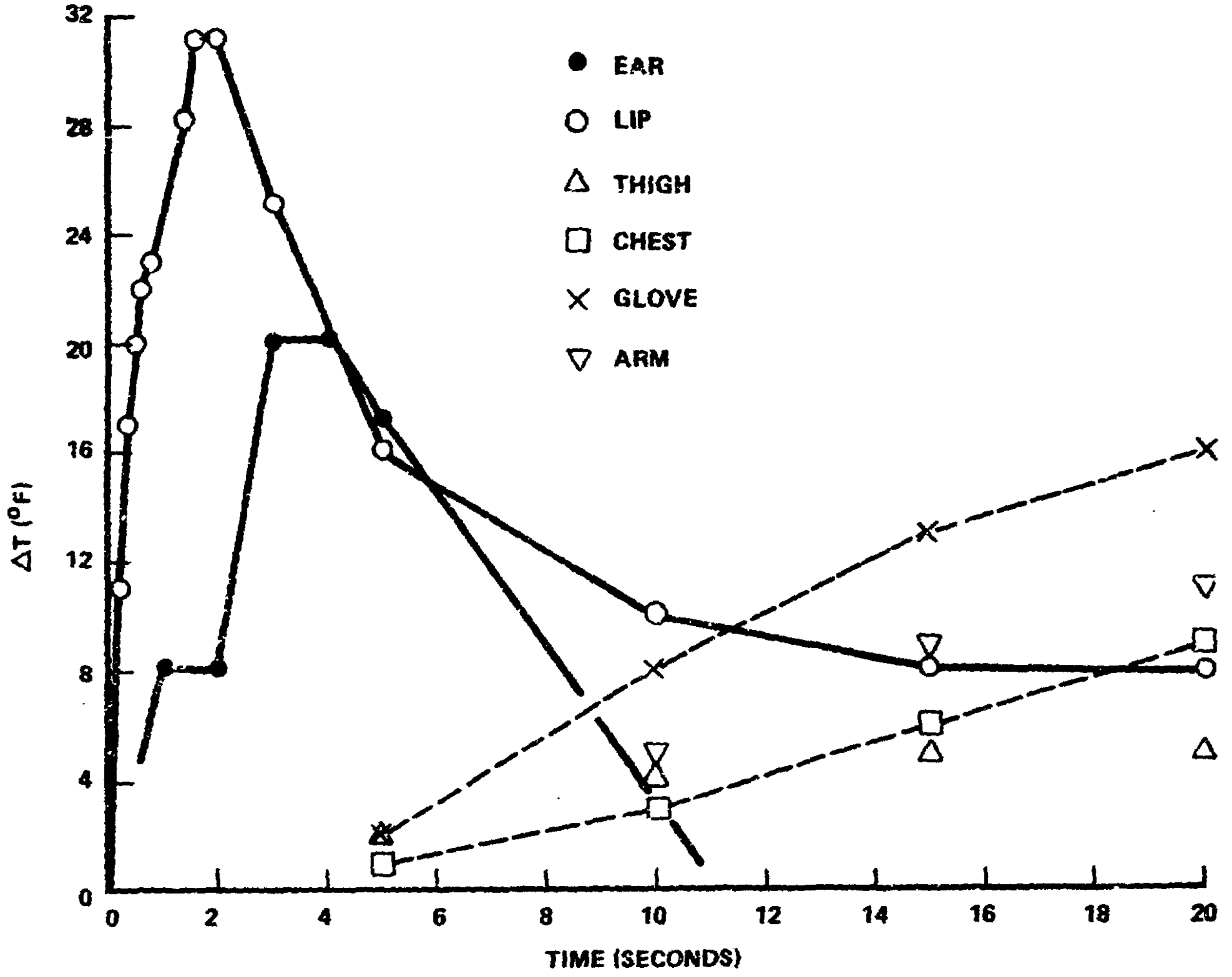


FIGURE 10
TEMPERATURE PROFILES INSIDE FIRE SUIT

10. CONCLUSIONS

A fire suit designed with two aluminized layers and a fiberglass felt has been shown to provide a more than adequate shielding against the accidental ignition of pyrotechnic in its most hazardous form - rapidly burning granules. Simpler and less costly designs seem feasible, if the double aluminized design is maintained by placing the second aluminized layer on the fiberglass felt and eliminating the second fabric layer.

Although this suit was especially designed for highly radiative pyrotechnic events, the double aluminized layer concept should be helpful in the lower temperature fire and furnace applications.

Some aspects of the new French regulation concerning the protection of workers with regards to the hazards of explosive activities from the manufacturer's point of view.

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by

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ABSTRACT

One of the most remarkable innovations of the French regulations consists in the obligation for the manufacturer to carry out a safety analysis before each change in his activity, to consult the Hygiene and Safety Workers Commitee and to obtain the prior French administration approval before applying the change if it is an important one, such as the start of a new facility, the manufacturing of new energetic materials or the use of new processes.

The main aims of this safety analysis are :

- detecting all explosive accident possibilities,

- assessing in each case the nature, the severity and the probability of the risks which the plant's personnel, the public and property are submitted to,

- determining the necessary measures to prevent accidents and to limit their consequences,

- demonstrating that the residual risk levels are within the thresholds fixed by the regulation for each kind of threatened entity.

The case choosen to present the manner in which the manufacturer meet with his obligations is the case of a new mixing facility designed to prepare composite propellant paste with at least one granular high explosive component.

It presents the main explosive hazards : fire, mass detonation, fragments and it allows to show all the aspects of the works carried out to design the new facility in accordance with the technical needs and with all fixed prescriptions :

- safety data gathering on equipments, processes, materials, materials classification and in processes classification,

- assessment of the possible hazardous zones in relation with these data, the energetic materials masses, the design of buildings and protections, the land configuration,

- assessment of the accident probabilities,

- demonstration that the project meets all the regulation requirements.

The carrying out of this work needs specific tests and experiments, the use of advanced safety analysis methods and codes like the "DENSECLA" and "PROJSEC" codes we have had to develop prior to the analysis to assess the hazards of fragments and projections.

INTRODUCTION

One of the most remarkable innovations of the new French regulations (References 1, 2, 3) consists in the obligation for the manufacturer to carry out a safety analysis before each change in his activity, to consult the Hygiene and Safety Workers Committee and to obtain the prior French administration approval before applying the change if it is an important one, such as the start of a new facility, the manufacturing of new energetic materials or the use of new processes.

The main aims of this safety analysis are to define the necessary conditions to prevent accidents and as it is quite impossible to avoid them completely, in spite of the previous conditions, to limit their consequences to a very low level, especially for personnel. This regulation has been developed both to make a disastrous incident impossible and to reduce the frequency and the consequences of any explosive accident.

The steps taken in this safety analysis are :

- detecting all explosive accident possibilities,

- assessing in each case the nature, the severity and the probability of the risks which the plant's personnel, the public and property are submitted to,

- determining the necessary measures to prevent accidents and to limit their consequences,

- demonstrating that the residual risk levels are within the thresholds fixed by the regulation for each kind of threatened entity.

The different criteria of conformity are not limited to the usual ones like "QUANTITY-DISTANCE TABLES".

Two important innovations have modified these traditional points of view :

- the first is that most of the regulation requirements are fixed in terms of results and not of means,

- the second is the fact that these requirements introduce a relation between the acceptable consequences of an accident and its probability of occurence and that, not only for the near and far environment. There are also requirements at the level of the working station directly concerned by the accident.

These last requirements have been shortly summarized through the two following rules which we use to prove that an elementary explosive facility called "a_0" is in accordance with these aspects of the regulation :

- The first, called "RULE OF CONFORMITY a_k Z_i P_j" allows us to show the conformity of the lay-out of an installation "a_k" (ten different kinds of a_k defined in table 1) located in the hazardous zones "Z_i" created by "a_0" (five kinds of "Z_i" defined in table 2) with the probability level "P_j" (five levels defined in table 3). The requirements to comply with are given by table 4.

- The second, called "RULE OF CONFORMITY in a_0 Z_1" allows us to show that the number of workers simultaneously present in the hazardous zones "Z_1" and "Z_2" of "a_0" with a level of probability greater than P_1 is in accordance with the regulations, i.e. roughly : maximum five if the probability of accident is "P_2" , maximum five if it is "P_3" but with less than 10 % of the working time, no personnel present if it is "P_4" or "P_5" .

APPLICATION EXAMPLE

To illustrate the manner used to perform the "SAFETY ANALYSIS" and to prove the conformity to the two previous rules, I will briefly present some aspects of the work carried out to design a new propellant mixing facility in our plant of Saint-Médard.

We needed a new mixing facility to prepare composite propellant paste with at least one 1.1 hazard class component. The amount of paste per unit operation was fixed to 3 000 kg. The choice of the mixer was given : a vertical one, already qualified for this kind of production and wellknown in our plant.

1 - FIRST STEP

The first step of the SAFETY ANALYSIS consists in detecting all explosive accident possibilities.

These possibilities are the consequences of the presence of sensitive, energetic materials (raw, intermediate and finished materials and wastes) which are submitted to the actions of processes in normal or abnormal conditions, in an environment which may be unfriendly and sensitive.

Materials

To assess them, it is necessary to set up the exhaustive list of all the energetic materials which may be present in the installation and to know very well their behaviours and their sensitivity to the different kinds of agression : mechanical, thermal, chemical, electrostatic, etc...

We use for that a procedure called I.S.P. (Integrated Safety Program) which has been developed to collect these characteristics and, if they are not available, to perform the tests or experiments necessary to obtain them. One of the main characteristics required for the analysis is for each material its classification in a risk division (table 5) eventually in relation with the level of confinement or in relation with another characteristic like the mass, the geometry, etc...

Processes

For each process, we have determined the maximum stresses applied to the material in normal and abnormal conditions.

At this point of the analysis, it is already possible to forsee the different possibilities of explosive accidents (e.g. : ignition by mechanical friction, initiation by impact, etc...), to assess margins of safety and to define critical stresses.

2 - SECOND STEP

The second step consists in assessing the nature, the severity and the probability of each potential accident.

The nature of the effect comes from the risk division of the materials in their environment (process, packaging, temperature, etc...) and from the nature of the stresses.

In our case, the presence of a high explosive component creates the hazard of mass detonation and consequently the risk of blast. The blast effect on the mixer, especially its bowl, on the different apparatus located near the mixer, on the raw material containers and on the building will give the risk of fragments and projections. As the final product is a propellant paste, we have also the hazard of combustion or deflagration and the risks of severe heat flux with a large amount of very hot gases in a confined space.

The severity

The severity comes from : the nature of the risk, the mass of energetic material involved in the accident, the environment (eventual presence of protections around the initiated load).

These informations allow us to determine a preliminary assessment of the extent of the different hazardous zones created by the mixing shop, using the equation which gives the radius of these zones as a function of the mass for each kind of hazard, on flat ground, without protection :

$$R_i = x_i \, Q^{1/3}$$

were R_i = the upper limit radius of the hazardous zone Z_i

x_i = factor dependant of "i" and of the division of risk of the energetic material (table 6).

For the evaluation of the thermal hazard zones we have taken the total mass of energetic material present in the mixing facility (figure 7) but for the blast effect, we increase this mass by a factor of 1.4 which is the upper value of the TNT equivalence of the propellant (figure 8).

The fire-hazard zones are completely contained in the blast hazard zones.

As equations to assess fragments and projections risks are only available for the case of ammunitions, we decided to design a protection to contain the most dangerous fragments, i.e. those which can be produced by the fracture of the bowl because they will be the most numerous and with the highest initial velocities.

To determine the characteristics of this protection and to prove its efficiency, we apply the "DENSECLA" code, especially developed by the "SNPE TECHNICAL SAFETY GROUP" for that purpose.

For a cylindrical explosive charge, placed in a steel case, this code gives the distribution of fragments in mass, energy and direction as a function of the explosive mass, the Gurney and Mott coefficients, the thickness and the nature of the steel (figure 9).

In our case, the result of the computation in the worst condition of initiation (at the base of the bowl) is that all the dangerous fragments will be emitted in an angle less than 12° with the horizontal plan.

So, with a convenient shield, the fragments hazard zones will be contained inside the blast hazard zones.

The probability of occurence

The different probabilities of accidents have been assessed on the base of our experience and analogic comparisons between the new materials present in the mixer and already wellknown materials in the same conditions.

Afterwards, we added a "FAILURE MODE AND EFFECT ANALYSIS" (F.M.E.A.) to improve this first assessment especially to take in account all the changes introduced by the new materials and the new equipments, to give more accurate safety specifications to design the equipments and to reach lower levels of probabilities (more than 200 failure modes analyzed).

As this analysis appeared to be insufficient to prove that the risk of mass detonation initiated by foreign bodies in the bowl was sufficiently low, we completed the work by carrying out a "FAULT TREE ANALYSIS" (F.T.A.) for this scenario.

Finally, we could justify a level "P_3" for the fire risk and the level "P_2" for the mass detonation risk.

At this step of the analysis, it was possible to define the lay-out of the new shop with its accesses in accordance with the "a_k Z_i P_j" and "a_0 Z_i" rules and to achieve the analysis of the measures taken to prevent the risks and to limit the consequences of an accident.

Measures taken to prevent the risks

They have been determinated from the previous risks analysis (Experience, F.M.E.A., F.T.A.) with a priority to the situations presenting the most important "SEVERITY, PROBABILITY" couples.

Various measures have been prescribed.
Among them :

- for materials handling : to cut off the risk of container and bowl fall ; all handling operations are feasible without hanging, only using lifts or elevators.

- <u>for the raw materials</u> : all raw materials have to be screened or filtered, before their introduction into the mixer bowl very close to it. The sieves have to be designed without the possibility of creating inside foreign bodies.

- <u>for the building</u> : design to avoid the possibility of getting foreign bodies which could fall into the bowl.

- <u>for the operating instructions</u> : to limit the exposure time of the open bowl to the environment, to check the use and the presence of tools, to clean and to check perfectly the apparatus and the mixer shop.

- <u>for the mixer</u> : to clean better the blades and the mixer-head in better working conditions, we asked the manufacturer to widely open the aft side of the mixer.

- <u>for the electrostatic discharge initiation risk</u> : generalized grounding, conductives floors, conductives shoes, personal conductivity system for daily checking.

Measures to limit the consequences

A number of measures were identified and prescribed to reduce the consequences. Some are given below for the main risks :

- The mixer building has been designed to contain the most dangerous fragments. It is barricaded with concrete walls and earth. (figure 10) ; the top of this rough work is designed at least at 20° above the bowl in the working position. This gives a margin of 66 % with regard to the 12° given by the "DENSECLA" Code.

- To limit the elevation of the walls and to remove the need of stairs to approach the mixer blades and head for cleaning operations, the mixer base has been placed 1,5 meter below the ground level.

- To reduce the number of projections and the associated risks, the upper parts of the building are made of light, easily fragmentable materials, such as wood and foam-concrete which are not able to give dangerous fragments. (These materials and their surface treatments have been tested to verify their impermeability and their compatibility with the energic materials).

- The choices made for handlings avoid the presence above the mixer of heavy travelling crane and steel beams, potential projection sources.

- To limit the risk of deflagration to detonation transition (DDT) we have equiped the mixer with a very efficient and reliable deluge system with IR and UV detection (total time between detection and water arrival in the bowl less than 150 ms).

This deluge system gives also the workers a protection against fire during their interventions.

Other measures have been prescribed to limit the consequences of a fire.

3 - LAST STEP : CONFORMITY DEMONSTRATION

This step consists in demonstrating from the previous technical informations (nature, probability, effects of the risks) that the residual risks which the workers in the mixer-shop and in the other facilities, the people and properties in the vicinity are submitted to, are in accordance with the regulations (rules "$a_o Z_1$" and "$a_k Z_i P_j$").

(In fact, the progression is iterative and not linear).

Rule "a_0 Z_1"

To satisfy this obligation, as the probability of incidents able to generate a "Z_1" is above "P_1" , we have to fix the amount of persons simultaneously present in the mixer shop to five without any limit of time for the less dangerous operations (P_2) - like handling and cleaning ; but as the probability is at the level "P_3" during the rotation of the blades or the up and down movement of the bowl, nobody will be present (during this period). The conformity is so realized without using the 10 % working time presence possibility. These operations are remotely controlled from a shelter located in the "Z_2" of the mixing station and design to protect the people inside at the level "Z_4" .

Rule "a_k Z_i P_j"

- We have two "a_1" , the upper remote control room and the place where the energetic materials and propellant wastes are stored after cleaning and before removal for disposal. This place has been choosen to be in "Z_2" , at the foot of the revetment. Its access is authorized only when the mixer is stopped. In complement, we verified that there was no risk of direct transmission of initiation between the charge of waste and the charges inside the mixing shop.

- We have several shops, storages and roads classified as- "a_2" facilities. None are in "Z_1" or "Z_2" except one road common to many shops which his partially in "Z_2" .

As we can affirm that the traffic on this way will give a presence during less than 10 % of the working time, this situation also complies.

- The situation of the offices classified as "a_3" , in "Z_4"- from the blast effect also complies since the probability of this risk is only "P_2" .

- The conformity is also verified in the vicinity : all houses and main roads are in "Z_5" or more distant and we don't find any large gathering place like a market, a school or a stadium in the "Z_4" and "Z_5" .

Reciprocally, we have to give the demonstration that the mixing station is not located in a forbidden hazardous zone coming from another explosive shop or from an other risk like a flamable solvent depot.

CONCLUSIONS

The SAFETY ANALYSIS prescribed by the new French regulation is an excellent mean to rationalize the numerous steps and choices which are to be achieved all along the design of new explosive facilities.

As the conformity criteria are very detailed and discriminating, dependent in particular both on the severity and the probability of the feared events, it is possible to design our facilities and to use them on one hand without inadequacy of mean and on the other hand, without overestimated protections, equipments and instructions.

As many requirements are formulated in term of results, it is possible to introduce innovations which improve safety in our plants with adequate, economical performances.

Briefly, the SAFETY ANALYSIS prescribed by the new French regulations, represents more than an obligation and a formality, it is principally an excellent method to improve safety.

REFERENCES :

(1) "décret 79846" dated September 28, 1979
(2) "arrêté" dated September 26, 1980
(3) "circulaire" dated May 8, 1981

TABLE 1

DESIGNATION OF INSTALLATIONS TO PROTECT FROM DONOR "a_0"

1. FACILITIES INSIDE THE PLANT

a_1	PYROTECHNICAL FACILITIES HAVING TO BE LOCATED NEAR "a_0"
a_2	OTHER PYROTECHNICAL FACILITIES AND INNER ROADS
a_3	INERT BUILDING

2. ROADS OUTSIDE THE PLANT

b_1	TRAFFIC $<$ 200 VEHICULES/DAY
b_2	TRAFFIC BETWEEN 200 AND 2000 VEHICULES/DAY
b_3	IMPORTANT TRAFFIC $>$ 2000 VEHICULES/DAY

3. BUILDINGS OR OTHER PLACES OUTSIDE THE PLANT

c_1	UNINHABITED, SHORT PRESENCE
c_2	INHABITED BY OR WITH PRESENCE OF PLANT PERSONNEL
c_3	OTHER FACILITIES, HOUSES,
c_4	GATHERING PLACES OF PEOPLE : MARKETS, SCHOOLS, HOSPITALS, DENSELY BUILT UP AREA.

TABLE 2

DESIGNATION OF HAZARDOUS ZONES

Z_i	PERSONAL INJURY	PROPERTY DAMAGE
Z_1	LETHAL INJURY IN MORE THAN 50 % OF CASES	VERY SEVERE DAMAGE
Z_2	SERIOUS INJURIES WHICH MAY BE LETHAL	SEVERE DAMAGE
Z_3	INJURIES	MEDIUM AND SLIGHT DAMAGE
Z_4	POSSIBILITY OF INJURIES	SLIGHT DAMAGE
Z_5	VERY LOW POSSIBILITY OF SLIGHT INJURIES	VERY SLIGHT DAMAGE

TABLE 3

DESIGNATION OF CLASSES OF PROBABILITY

P_i	LEVEL	ANNUAL FREQUENCY	EXEMPLE
P_1	EXTREMELY	$< 10^{-4}$	STABLE EXPLOSIVE PACKED FOR TRANSPORT IN A STORAGE.
P_2	VERY RARE	$< 10^{-3}$	PACKING, CASTING HANDLING.
P_3	RARE	10^{-2}	NITRATION, MIXING, DRYING, MACHINING OF SENSITIVE, ENERGETIC MATERIAL.
P_4	RATHER FREQUENT	10^{-1}	OPERATIONS ON VERY SENSITIVE MATERIALS, PRODUCTION OF PRIMARY EXPLOSIVES.
P_5	FREQUENT	$> 10^{-5}$	MIXING, COMPRESSION OF PRIMARY EXPLOSIVES.

TABLE 4

RULES OF CONFORMITY "a_k Z_i P_j"

PROBABILITY / HAZARDOUS ZONE	P_1	P_2	P_3	P_4	P_5
Z_1	a_0	a_0	a_0 (x)	a_0 (xx)	a_0 (xx)
Z_2	a_1 a_2	a_1 a_2 (x)	a_1	a_1 (x)	a_1 (xx)
Z_3	a_1 b_1 c_1 a_2 a_3	a_1 b_1 c_1 a_2	a_1 a_2	a_1	a_1 (x)
Z_4	a_1 b_1 c_1 a_2 b_2 c_2 a_3	a_1 b_1 c_1 a_2 b_2 c_2 a_3	a_1 b_1 c_1 a_2	a_1 a_2	a_1
Z_5	a_1 b_1 c_1 a_2 b_2 c_2 a_3 b_3 c_3	a_1 b_1 c_1 a_2 b_2 c_2 a_3 b_3 c_3	a_1 b_1 c_1 a_2 b_2 c_2 a_3 b_3 c_3	a_1 b_1 c_1 a_2 b_2 c_2 a_3 b_3 c_3	a_1 b_1 c_1 a_2 b_2 c_2 a_3 b_3

(x) = presence limited to maximum 10 % of the working time.
(xx) = no presence allowed [illegible]ed in particular circonstances.

TABLE 5

HAZARD CLASS

CLASS	DIVISION	HAZARD
1	1	MASS-DETONATING
1	2	NON MASS-DETONATING FRAGMENT PRODUCING
1	3.a	MASS FIRE - HIGH BURNING RATE
	3.b	MASS FIRE - LOW BURNING RATE
1	4	MODERATE FIRE NO BLAST
1	5	MASS-DETONATING LOW SENSITIVITY

TABLE 6

MAXIMUM RADIUS Ri FROM THE HAZARDOUS ZONE Z_i AS A FUNCTION OF "Q" kg AND HAZARD CLASS

Hazard Classification		HAZARDOUS ZONES (m)				
		Z_1	Z_2	Z_3	Z_4	Z_5
1.1.		5 $Q^{1/3}$	8 $Q^{1/3}$	15 $Q^{1/3}$	22 $Q^{1/3}$	44 $Q^{1/3}$
1.2	ammunition $\leqslant$ 60 mm	15	90	200	max. (60 $Q^{1/6}$) 300	max. (120 $Q^{1/6}$) 600
	ammunition > 60 mm	25	135	300	max. (75 $Q^{1/6}$) 400	max. (150 $Q^{1/6}$) 800
1.3	1.3.a	2,5 $Q^{1/3}$	3,5 $Q^{1/3}$	5 $Q^{1/3}$	6,5 $Q^{1/3}$	
	1.3 b	1,5 $Q^{1/3}$	2 $Q^{1/3}$	2,5 $Q^{1/3}$	3, 5 $Q^{1/3}$	
1.4			max. (0,5 $Q^{1/3}$) 5	10 $Q^{1/3}$	25 $Q^{1/3}$	

FIGURE 7

FIRE HAZARD ZONES

Mass Q : 3 000 kg

Class : 1.3 b

$R_1 = 1.5\ Q^{1/3} = 22$ m

$R_2 = 2\ Q^{1/3} = 29$ m

$R_3 = 2.5\ Q^{1/2} = 36$ m

$R_4 = 3.25\ Q^{1/3} = 47$ m

FIGURE 8

BLAST HAZARD ZONES

Mass Q : 3 000 kg
Class : 1.1
TNT eq. factor : 1,4
TNT eq. mass Q' : 4 200 kg

$R_1 = 5\ Q'^{1/3} = 81$ m

$R_2 = 8\ Q'^{1/3} = 130$ m

$R_3 = 15\ Q'^{1/3} = 242$ m

$R_4 = 22\ Q'^{1/3} = 355$ m

$R_5 = 44\ Q'^{1/3} = 710$ m

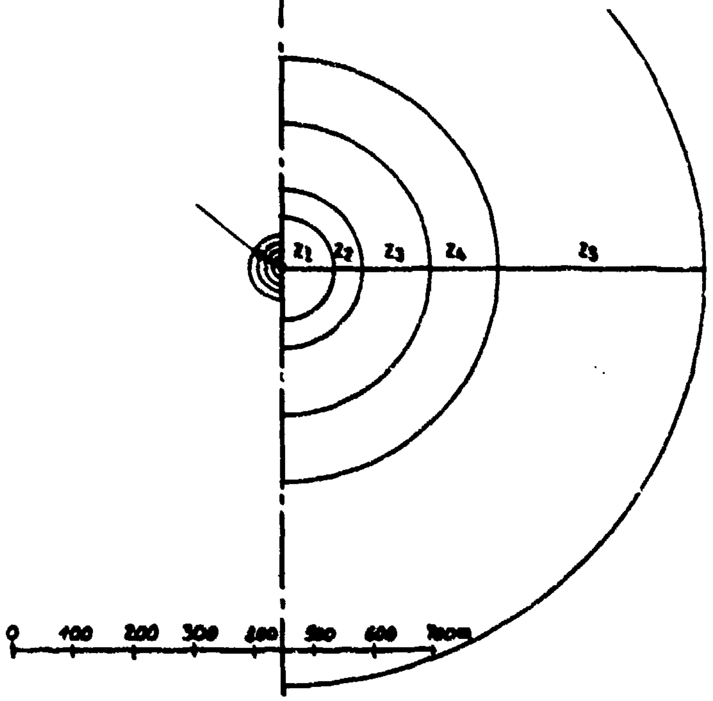


FIGURE 9

DENSECLA CODE

DENSITY AND ENERGY OF FRAGMENTS AS A FUNCTION OF "d" ON VERTICAL AND HORIZONTAL SURFACES.

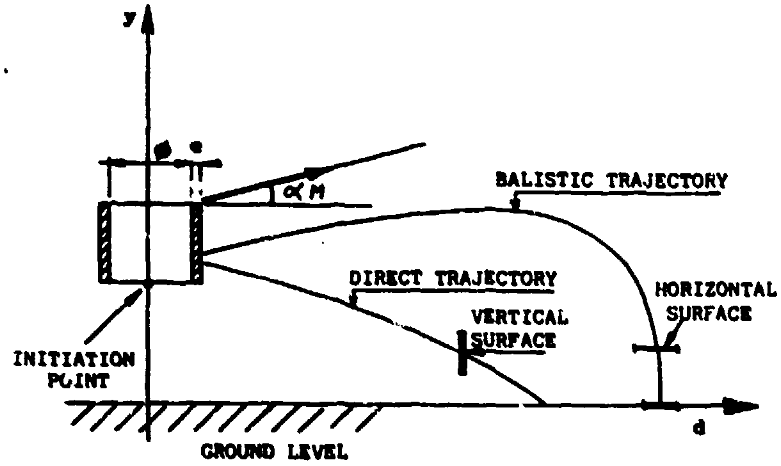


FIGURE 1C

MIX STATION

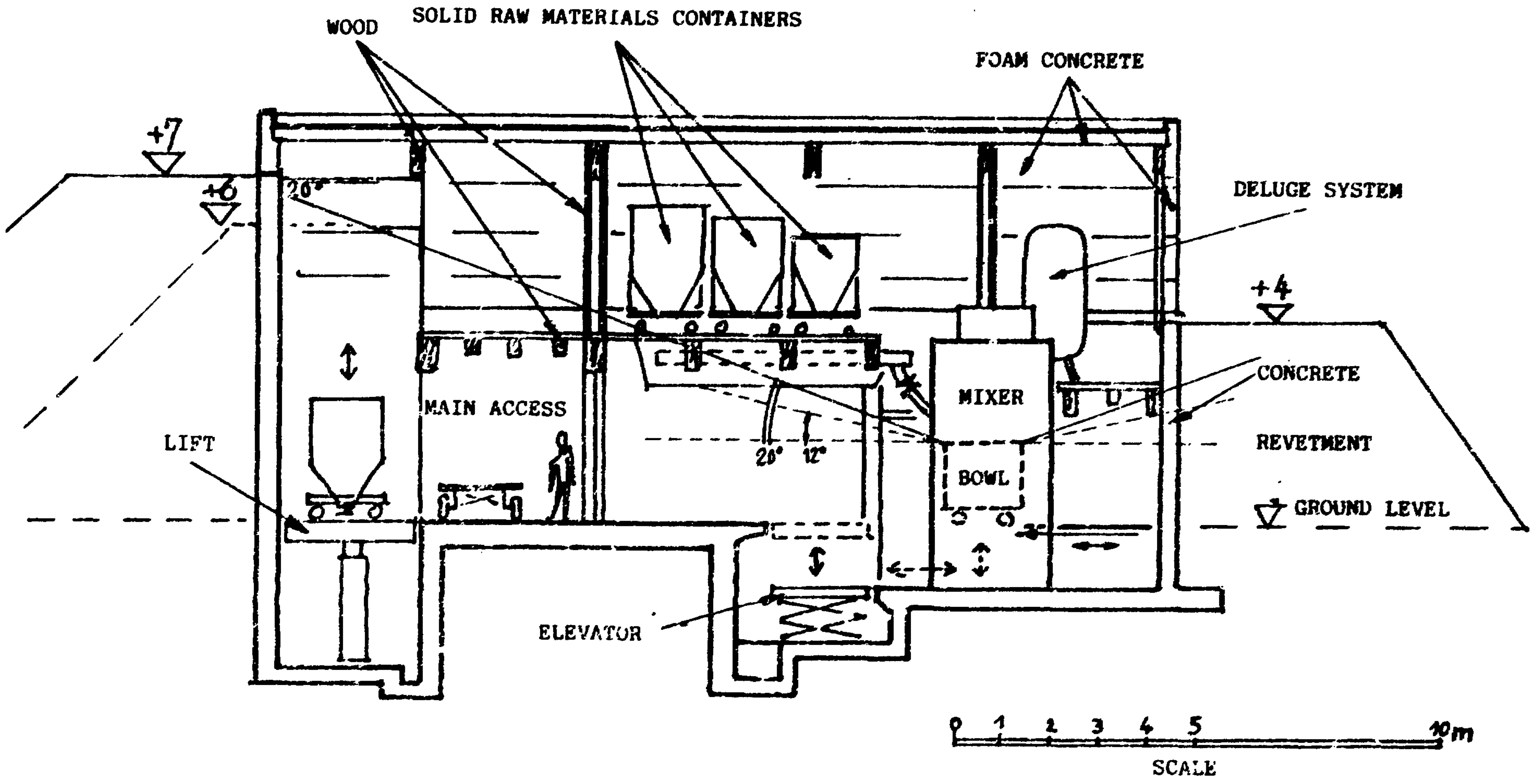


FIGURE 10'

MIX STATION

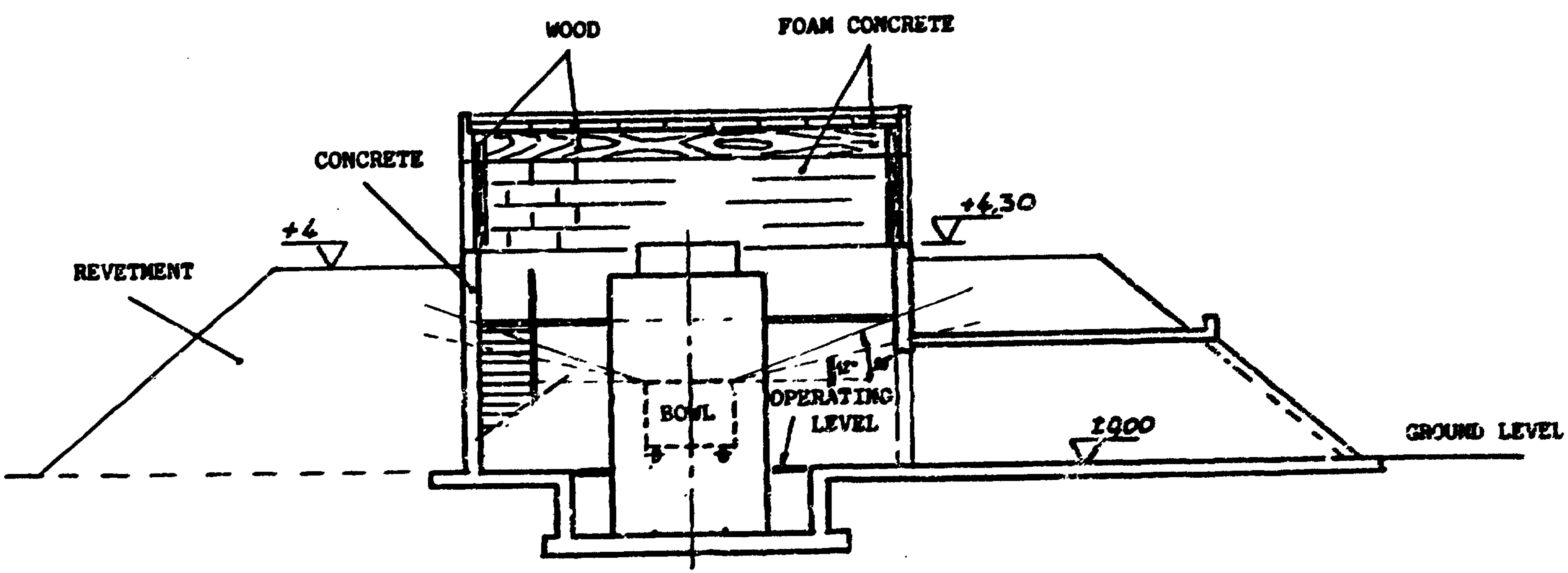


FIGURE II'

LAY-OUT

(RULE "a_k Z_i P_j")

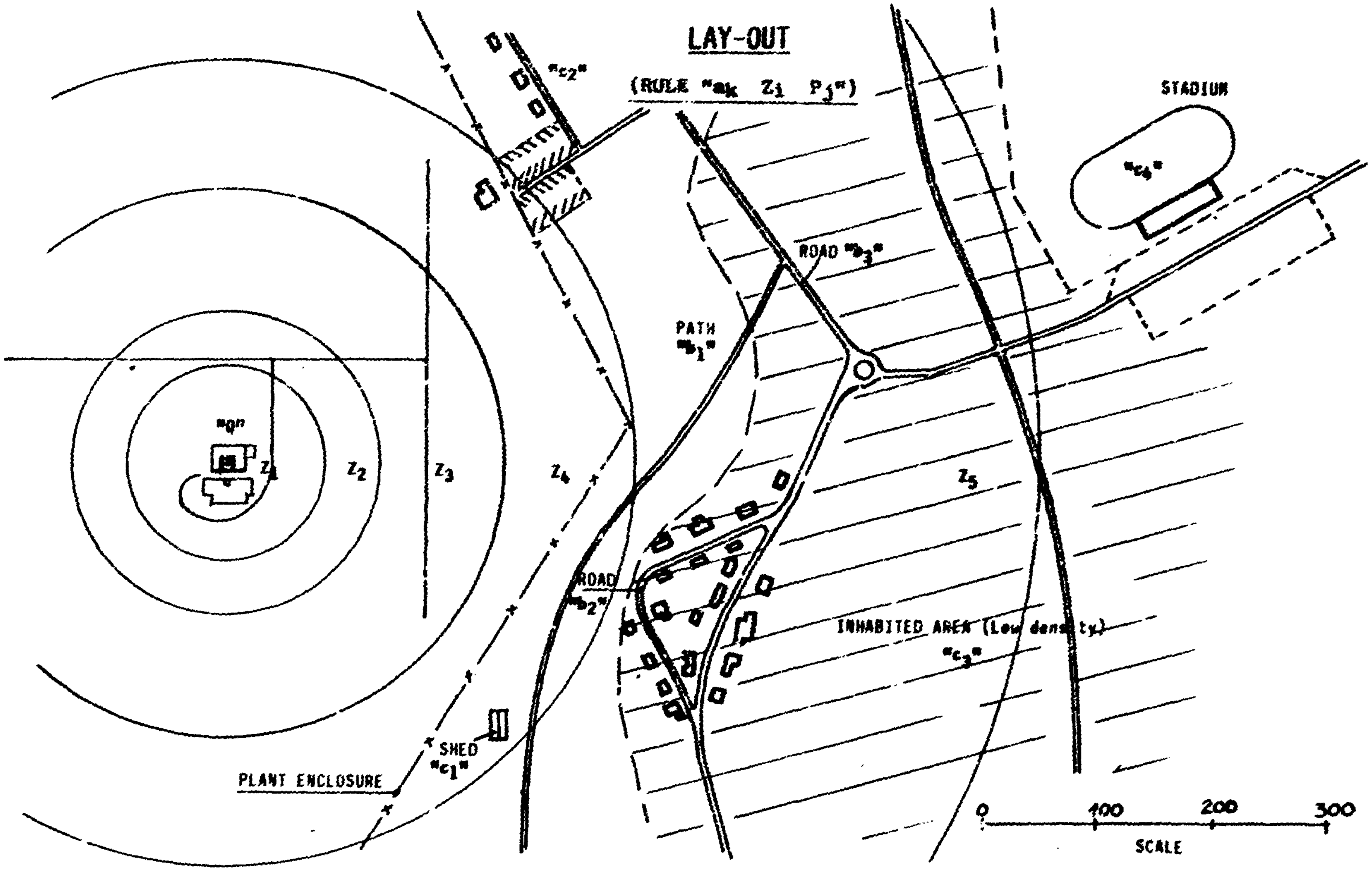
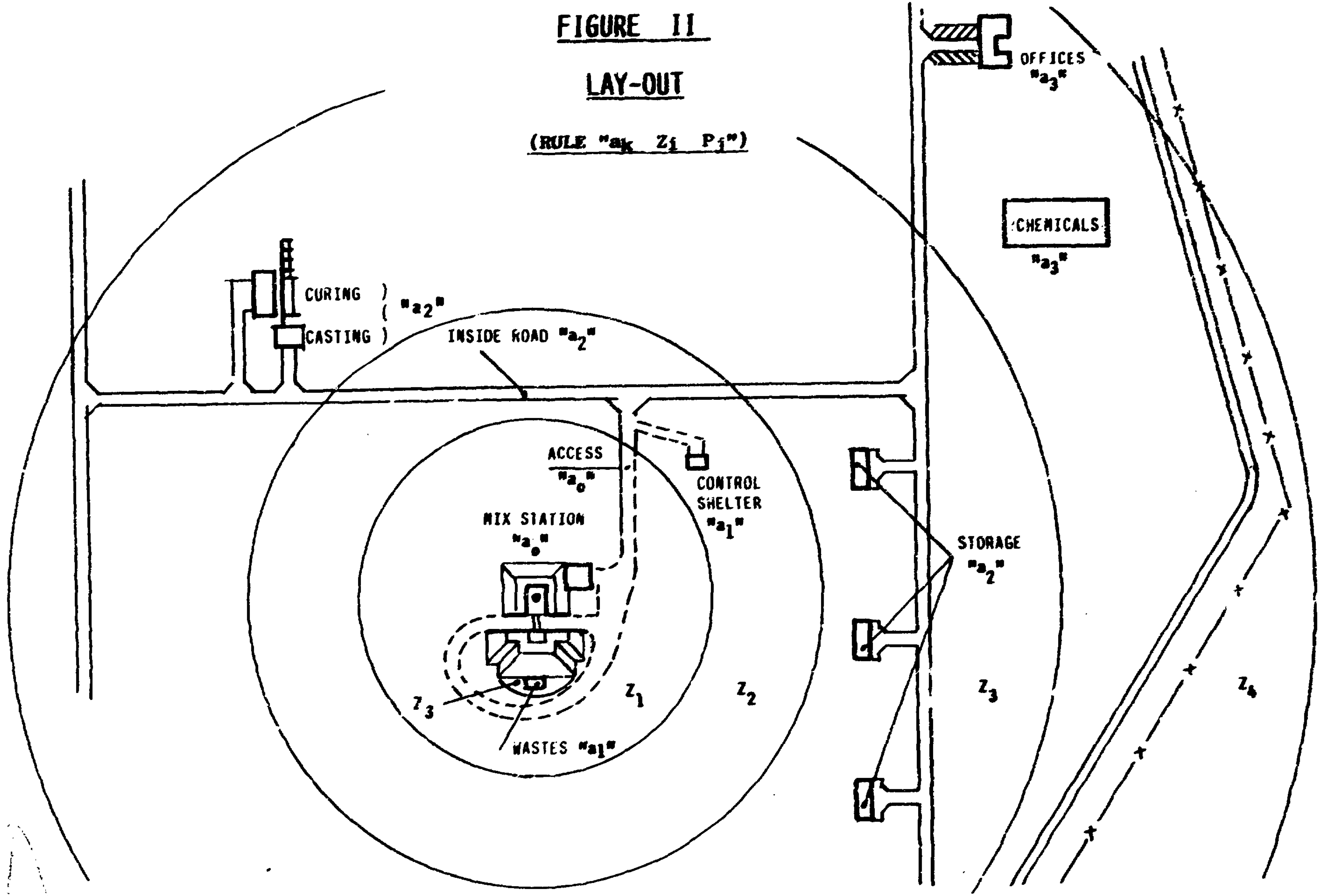


FIGURE II

LAY-OUT

(RULE "a_k Z_i P_i")



A SIX YEARS PRACTICE IN THE ENFORCEMENT OF THE NEW FRENCH EXPLOSIVE SAFETY REGULATION

BY

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ABSTRACT

French Department of Labour has edicted in 1979 new regulations in order to protect workers in explosive or pyrotechnic establishments. For the enforcement of this new regulations the Labour Inspectorate has received assistance from the Inspectorate of Armaments for propellants and explosives of the French D.O.D.

The aim of INGENIEUR GENERAL R.V. AMIABLE, DEPUTY INSPECTOR FOR PYROTECHNIC SAFETY at the FRENCH INSPECTORATE of Armaments is :

- to make a short history of the French safety regulation concerning explosive or pyrotechnic establishments,
- to explain the main characteristics of the new regulations; and
- to discuss the benefits and the disadvantages of the new system in the light of a six years pratice, first from the point of view of the French Inspectorate and second from the one of the manufacturers.

1. - REGULATING BEFORE 1980

1.1 - THE PREHISTORIC TIMES : 1875 - 1955

Before 1955 there was no one specific law or decree in FRANCE concerning the protection of workers against special risks to which they were subjected in establishments dealing with gun powder, propellants, explosives, pyrotechnics or ammunitions.

However we had the law of the 19 th of december 1917 concerning the establishments which had to be classified for the protection of the environnement. The most dangerous of them, in particular explosive or pyrotechnical factories, were submitted to a preliminary official authorisation before opening ; this authorization was given by an order which constrained the head of the classified establishment to take a number of precautions for protection of the vicinity, of course, but also of the workers of the factory. This safety regulations could be noticeably different according to the place or the time.

Moreover there was an older particular way of regulating which concerned specially the dynamite factories and which was fixed by the law of the 8 th of august 1875 and the decree of the 24 th of august 1875 with the view to protect vicinity and workers.

In that good old days Frenchmen dealing with explosives, propellants or pyrotechnics made preliminary risk analysis and they chose the safety ordering and devices with reference to the three old and famous principles of the FRENCH POWDER MAN :

- FIRST to limit the risks
- SECOND to separate the risks
- THIRD to superposate the safety devices.

1.2 - THE BIRTH OF MODERN TIMES IN 1955

A modern regulation concerning specially the protection of workers in factories dealing with explosive or pyrotechnical matérials was born in FRANCE in 1955. It took the form of a decree signed by the Prime Minister, the Minister of Labour and Minister of Defence, The Council of State having been heard on the matter ; this decree was the decree n° 55.1188 of the third of september 1955.

The main caractéristics of this new specific regulation were the followings :

1. The head of the explosive or pyrotechnical establishment had to establish general safety regulations, regulations concerning each pyrotechnic room and special regulations specific to each work, location or station, and to submit this safety documents for prior approval to the district Director of Labour and Employment, who consulted the Inspector for Explosives and Propellants.

2. The head of the establishment had to get the permission of the district Director of Labour, who consulted the Inspector for Explosives and Propellants, before beginning to produce or handle explosive materials with a new apparatus.

3. He was required moreover to satisfy a number of other means obligations concerning :

   - distribution of buildings
   - type of constructions
   - exits and passageways
   - floors, walls, ceilings, frameworks
   - electrical installations
   - heating installations
   - equipment
   - raw materials
   - wastes
   - individual safety equipment
   - fire-fighting
   - maintenance and repair work
   - proficiency of managers and workers.

The general safety regulations of the factory had to include more especially :

1. Prohibition to smoke, carry any smoker's articles, naked flames, incandescent objects, matches or any other means of creating flame.

2. Prohibition of any employee for going to an other work location - except personnel representatives subjected to the observation of the special safety regulations.

3. Obligation for the personnel to wear, during working hours, clothing, hats, slives and other personnal safety accesories supplied by the head of the establishment.

4. Prohibition of personnel to remove explosive materials or objects.

5. The measures to be observed for driving and parking vehicles of all types within the pyrotechnic enclosure.

6. General regulations to be observed in case of fire.

Moreover each work location or room safety regulation had to include :

1. The maximum quantities of explosive materials or objects and of their components which might be found in the room or at the work location, and, if necessary, at each work station.

2. The maximum number of persons which might deal with them.

3. The hand tools to be used therein.

4. The procedures to be used and the operations to be forbidden therein.

5. The procedures to be followed in case of fire, thunderstorm, or lighting or power failure.

6. Particular prescriptions for the room or the work location, more specially the measures to be observed for neutralization on the place or collecting, conserving with the view to dispose of the production wastes.

All this new official prescriptions resulted from the French experience gained during the prehistoric period thanks to preliminary risk analysis before explosive or pyrotechnic accidents and,may be more,owing to posterior analysis.

It is important to note that a lot of technical requirements enacted as obligations of means by the decree n° 55.1188 flowed from this risk analyses and moreover reflected accurately the state of the art in FRANCE during the fiftees.

The main advantages which the French national authorities were waiting for were the followings :

1. To deal with the little establishments which were not concerned in the past by the law and the decrees related to the protection of the environment.

2. To make more uniform the prescriptions concerning the explosive and pyrotechnical safety inside the factories.

3. To ensure enforcement of up-to-date technical safety requirements in all the explosive and pyrotechnic establishments, including the little ones, with a view to decrease the probability of occurency and the gravity of the dangerous effects of the accidents.

4. To aim at the same result thanks to the obligation of establishing safety regulations by the head of the establishment and obtaining the approval of the district authorities.

5. To give to the French authorities the means of verifying the existence of such safety regulations and in the same time their quality, thanks to the consultation of the Inspector for Explosives and Propellants.

6. To give also to the same the mean of controlling the use of new machines and prohibiting the use of too much dangerous.

1.3 - TWENTY FIVE YEARS WITH THE DECREE N° 55.1188

The enforcement of the decree n° 55.1188 contributed to maintain during many years a satisfying level of safety inside the factories dealing with explosives, propellants or pyrotechnics, facing the danger inhering in new materials more energetic and sensible, and in objects more complex.

In the same time new risk analysis tools were created and applied to the explosive and pyrotechnic field (fault trees, failure mode and critical effects analysis, ...) and the three principles of the "FRENCH POWDER MAN" became five :

- FIRST to know the risks
- SECOND to limit the risks
- THIRD to separate the risks
- FOURTH to superposate the safety devices
- FIFTH to integrate the safety in the design.

Parallely the state of the art progressed in the matter of technical means able to protect the workers inside the factories dealing with explosive matérials, making thereupon the decree of 1955 look older.

On their side the French authorities had some difficulties to appreciate correctly the submitted safety regulations and the authorization requests concerning new machines because they had no information about the preliminary risks analyses which had justified the choices of the heads of establishment.

Unfortunately terrible accidents occured in FRANCE during the seventies in several factories dealing with single base propellant, with dynamites and with pyrotechnic compositions.

At the same time the French Government had decided to increase the protection of workers thanks to a new general law and new specific decrees.

All that was the reason why a new decree appeared in 1979 in the French explosive and pyrotechnic field to take the place of the decree of 1955.

2. - THE NEW FRENCH EXPLOSIVE SAFETY REGULATION

2.1 - THE DECREE N° 79.846 OF THE 28 th OF SEPTEMBER 1979

The decree n° 79.846 has been signed, like decree n° 55.1188, by the Prime Minister, the Minister of Labour and the Minister of Defence, the Council of State having been heard on the matter.

The main caracteristics of this new decree are the followings :

1. The heads of the establishment, when planning a new fabrication, the use of new processes, the construction or modification of premises, the creation or modification of an installation, the fitting-out of a work location or station likely to have an effect on the safety of employees or the use of new means or systems of transport in the establishment, shall carry out a safety analysis or shall bring existing safety analysis up-to-date :

   Tending to determine all the possibilities of pyrotechnic accidents and to establish, in each case, the nature and gravity of the risks incurred by the establishment's employees ;

   Determining the measures to be taken to prevent accidents and to limit their consequences. (1)

   The heads of the establishment shall consult the health and safety committee concerning the study, or failing this, the labour delegates, as well as the workers' delegates for safety appointed under the above law of 8 april 1938 when such exist.

2. This safety analysis, to which is added the report of consultation of the Health and Safety Committee, shall be submitted for prior approval to the district Director of Labour and Employment, who consults the Director of Technical Inspection of Armaments for Powders and Explosives. The district Director shall make his decision known to the head of the establishment within three months from receipt of the approval request. He may however, by decision with justification, set a new deadline if required by examination of the file.

(1) Concerning the installations existing on the date of entry into force of the decree n° 79.846 the heads of establishment had to prove that maintenance of these installations in their present condition did not involve any significant risk.
They had to give the proof thanks to a safety analysis carried out in the same conditions as for new installations.

He may also, by justified decision, request the head of the establishment to carry out or to have carried out, at the cost of the company, and by a competent organization, additional tests necessary for the assessment of potential risks and of the effectiveness of the planned means of protection.

The three-month period shall begin again from the date on which the district Director has gained familiarity with the results of these tests.

In the absence of an answer from the district Director within the deadlines set, the head of the establishment may, in conditions resulting from the safety analysis, implement the planned operations. Sould be dispute one of the decisions taken by the district Director in application of this Article, he shall approch the Minister reponsible for Labour, for decision.

3. The procedures are defined by the head of the establishment in accordance with the conclusions of the safety analysis, and shall be consigned in service instructions.

4. Relying on the conclusions of the safety analysis, before implementing the operations which they cover and after consultation with the health and safety committee or, failing this, with the personnel delegates, as well as the workers' delegates for safety where they exist, the head of the establishment shall establish :

General safety regulations ;

Regulations concerning each pyrotechnic room ;

If required, special regulations specific to each work location or station.

5. The general safety regulations of the establishment have to include the same prescriptions as those enacted by the previous decree, plus the prohibition to proceed to pyrotechnic premises for operations not covered by instruction or regulations in force and measures to be observed for the movement of personnel within the pyrotechnic enclosure.

The regulations concerning each pyrotechnic room shall specify the same rules as previously, with some precisions.

Likewise the instructions specific to each pyrotechnic work location or station shall specify the previous rules concerning equipment for individual protection and hand tools, plus mobile equipment.

6. In the establishments covered by this Decree, the safe distance between two buildings or installations of the pyrotechnic enclosure, and between one of these buildings or installations and a building or installation outside the pyrotechnic enclosure, shall be such that the transmission or propagation of an accident is highly improbable, and that in case of accident sustained by a building or installation, the employees other than those who are found therein shall be subject to a limited risk.

If a building has a blast discharge façade, no other building shall be placed facing this façade unless it is suitably protected.

Ministerial Orders set the requirements applicable for determining the minimum safe distance to be observed, taking account of the type and quantity of explosible materials and objects, the activities performed, and the natural or artificial protection systems which may exist between the buildings or installations.

7. The head of establishment has moreover to satisfy a number of means obligations which concern the same points as previously, plus :

- doors, windows and stairways
- personnel movements
- air-conditionning
- ventilation
- risks of electrostatic origin
- transport and storage within the establishment
- training and information of personnel.

A number of previous obligations are determined more precisely and completed.

2.2 - THE MINISTERIAL ORDER OF THE 26 th OF SEPTEMBER 1980

The Ministerial Order of the 26th of september 1980 has been edicted to fix the rules for determining safe distances pertaining to explosive and pyrotechnic installations

In the same time it gives a safety analysis methodology and it supplies criteria able to quantify the danger for each exposed site (E.S.) in the vicinity of a potential explosion site (P.E.S.) and also to fix minimal levels of pyrotechnic safety for each E.S..

First, the head of establishment has to classify each explosive material or object produced or handled in his factory in a risk division of the UNO class I and, if applicable, in a compatibility group. This classification must be made by using a series of tests and by taking account of effective specific operating conditions, for example confinement of a material in a machine.

Second, he must determine the danger zones generated around each P.E.S. with reference to the classification of five danger zones Z1, Z2, Z3, Z4, Z5 defined by the Order and by calculating distances by the means of formulae given by this Order for each type of dangerous effect (explosion in mass, projection, heat radiation). Of course this distances shall be increased if specific conditions are liable to aggravate the danger or may be reduced if the land configuration or the installation of effective protection systems reduce the gravity of the danger.

Third, the probability of a pyrotechnic accident shall be estimated in each elementary pyrotechnic installation with reference to five degrees P1, P2, P3, P4 et P5 (extremely rare, very rare, rare, fairly frequent or frequent).

Fourth, the different categories of installations to be protected against the effects of a pyrotechnic accident liable to occur in an elementary pyrotechnic installation "a_0" have to be listed and classified "a_1", "a_2" or "a_3".

Fifth, the triplet (a_k, Z_i, P_j) determines the quantified pyrotechnic risk generated by each P.E.S. "a_0" against it vicinity of E.S. "a_k" and it permits at the same time to know with precision and objectivity and to announce the residual pyrotechnic risks to be generated by the new activity.

Sixth, the head of establishment shall verify that such residual pyrotechnic risks are not greater than the minimal safety levels required, which are given in a table of "installation layout conformity "under the form of triplets (a_k, Z_i, P_j). If not he has to modify his project with the aim to obtain the conformity required by the new safety regulation.

It is important to note that such a methodologic step answers an essential obligation of results required by the new French safety regulation, letting liberty for the means to achieve it.

Moreover and parallely the head of establishment has to consider the security of the different persons present in each P.E.S. and to limit their number in each "a_0" relating with the gravity Z_i and the probability P_j.

The entire text of the Ministerial Order is annexed to this paper.

2.3 - THE MEMORANDUM OF THE 8 th OF MAY 1981

The Directorate of Labour Relations at the French Ministry of Labour has published in may 1981 a memorandum which was intended to supplement and, where applicable, to discuss some of the provisions of the Ministerial Order edicted the year before.

This memorandum gives on that occasion a lot of advices which are precious for carrying out the safety analysis ; they concern mainly :

- the classification of explosive materials or objects, the tests and the inclusion procedure
- protective systems and reduction of the danger zones Z_i
- estimation of the probability P_j of pyrotechnic accident
- risk analysis of propagation in case of a pyrotechnic accident.

3. - BENEFITS AND DISADVANTAGES TO GET OUT OF THE ENFORCEMENT OF THE NEW REGULATION

3.1 - FROM THE POINT OF VIEW OF THE FRENCH NATIONAL AUTHORITIES

3.1.1 - Expected benefits

French national authorities expected some important benefits in the matter of protection of the workers :

a) a reduction of the probability and gravity of the pyrotechnic accidents thanks to up-to-date technical means obligations.

b) an other similar reduction owing to better preliminary risks analysis in the new framework of required safety analysis inducing better specific safety regulations and safer procedures.

c) a working participation of the health and safety committees in the safety analysis.

d) the possibility to appreciate the quality of the risk analysis work carried out by the heads of establishment and the safety measures flowing from it, owing to the study of the submited documents.

e) a better knowledge by heads of establishment and in consequence by French authorities of the pyrotechnic residual risks thanks to the new and original means of quantification by the triplet (a_k, Z_i, Pj).

f) the correlative ability to enforce the respect of minimal pyrotechnic safety levels inside each potential explosion site "a_0" and at each exposed site "a_k" in the vicinity.

3.1.2 - Obtained benefits six years after

The study at the French Inspectorate for Explosives and Propellants of several hundreds of safety analyses carried out by heads of establishment since 1980 allows this authority to think that most people are able now to make good safety analyses by the new way and correlatively to reduce adequately the pyrotechnic risks in their factory and to announce in the same time the quantified residual pyrotechnic risks.

In more and more establishments the health and safety committee contributes to day diligently and profitabily to carry out good safety analysis.

The task of verification by the French authorities of the pyrotechnic safety levels thanks to the examination of submitted documents appears easier and more interesting than before 1980.

The final aim consisting in the respect by the head of establishment of quantified minimal safety levels and the verification of this respect by the national authority is reached. However a number of years of supplementary practice will be necessary to be sure of result, more especially in the matter of pyrotechnic disasters.

3.1.3 - Appeared disadvantages

To study and to verify all the files of new type is a hard task to perform by the French Inspectorate. Further this task was notably made more difficult during the first years because there were a number of insufficiency in the form and the matter of this files.

Moreover this task was largely made heafier in the same time because many heads of establishment submitted in addition for approval, safety analysis carried out for the installations existing on the date of entry into force of the new regulation (1).

It is not always easy to appreciate the contents of safety analysis from a parisian office and by reading a file. Happily the Inspectorate engineers are in contact with the manufacturers and they go periodically in the establishments to make visits of safety inspection.

A number of divergences also appeared for interpreting some technical points of the new regulation. The French Inspectorate tried to solve this delicate problem and to constitute a jurisprudence.

(1) Such safety analysis had not to be submitted for approval but French authorities accepted to deal with them like with the others with te view to aid the heads of establishment.

The practice of the new regulation has quickly shown that the criteria which had been chosend in the Ministeral Order with the view to determine the projection danger zones were not appropriate to many real situations, for example explosion of a tank full of explosives or bursting of a missile propelling. The French authorities will have to ameliorate the present regulations.

3.2 - FROM THE POINT OF VIEW OF THE MANUFACTURERS

3.2.1 - Found disadvantages

Many heads of establishment think that it is a very heavy task to carry out safety analysis by the new method and to constitute the corresponding files. It needs much time ... and time is money !

The enforcement of the new regulation has incited a number of manufactures to design and to construct new types of pyrotechnic buildings. These new constructions are certainly more sure for the workers but they are also certainly more expensive to build.

The new regulation has created a hard requirement concerning the classification of each material or object produced or handled.

To execute series of tests with taking account of all the effective specific operating conditions induces sometimes to make a very great number of experimentations which consume much time and money.

The time-limit of three months allowed to the French authorities to examine the files and to agree or not, is not always quite compatible with good fulfilment of contracts and commercial dynamics.

The pertinence of some technical criteria fixed by the Ministerial Order has been contested, more specially the criterion to determine the projection danger zone and the scale with five degrees of probability.

3.2.2 - Observed benefits

To have to try to determine all the possibilities of pyrotechnic accidents induces deeper thoughts of the responsible hierarchic line.

To have to receive a preceding safety approval for a new installation brings the manufacturer to integrate sooner and better the pyrotechnic safety in his project.

To have to classify the materials and objects with taking account of the effective specific operating conditions induced many safety trials and will increase the knowledge of real explosive risks.

Last but not least, the existence of official safety criteria utilizable by the heads of establishment for recognizing in advance the character acceptable or not of a situation in the matter of explosive or pyrotechnic safety appears more and more like a precious tool for design, for management and social dialogue.

ANNEX to the paper of R.V. AMIABLE

MINISTRY OF LABOUR AND PARTICIPATION

RULES FOR DETERMINING SAFE DISTANCES PERTAINING TO PYROTECHNIC INSTALLATIONS

26-09-1980

The Minister of the Interior, the Minister of Defence, the Minister of the Environment and Quality of Life, the Minister of Labour and Participation, the Minister of Industry and the Minister of Transport,

Considering Chapter III of Book II of the Labour Code, especially Article L.231-2 (§ 2);

Considering Law No.70-575 of 3 July 1970 concerning reforms of the regulations governing gunpowders and explosive substances;

Considering Law No.76-663 of 19 July 1976 concerning installations classified for the protection of the environment;

Considering Decree No.79-846 of 28 September 1979 concerning public administration regulations governing the safety of workers against special risks to which they are subjected in pyrotechnic establishments, and especially Articles 1, 3, 14 and 27;

Considering the opinion of the Commission on Explosive Substances;

Considering the opinion of the Higher Council on the Prevention of Occupational Hazards,

[illegible] following:

SECTION 1 GENERAL

Article 1

The present Ministerial Order applies to all establishments or parts of establishments covered by Article 1 of Decree No.79-846 of 28 September 1979 mentioned above.

It sets the rules to be observed, in accordance with the provisions of Article 14 of the above-mentioned Decree No.79-846, for determining safe distances to be maintained between two installations when one of them may be the source of a pyrotechnic accident.

The term "installations" applies to work locations, workshops, depots, storerooms, located inside or outside a pyrotechnic enclosure, as well as structures or potential sites of human activities located in their environment and belonging to a pyrotechnic establishment or not.

The term pyrotechnic accident is applied to any explosion, combustion or decomposition of explosible materials or objects not resulting from the normal operation of the installation where it occurs, and liable to cause personal injury and property damage.

Article 2

The safe distances to be maintained between the installations mentioned in Article 1 above vary according to the type and quantity of explosible materials or objects involved, the types of operation performed on these materials or objects, and the effectiveness of the protective systems placed between the installations.

In this Ministerial Order, they are considered as depending on:

(1) The gravity of the effects of a pyrotechnica accident.

(2) The probability of such an accident.

SECTION 2 CLASSIFICATION OF EXPLOSIBLE MATERIALS OR OBJECTS

Article 3

Explosible materials or objects make up Class 1 of dangerous goods and are classified as follows:

by risk divisions, depending on the types of effect of their explosion or their combustion, or according to their degree of sensitivity,

compatibility groups, according to the specific type of additional risk which they may incur when in the presence of materials or objects belonging to other groups.

A RISK DIVISIONS

Article 4

The risk divisions, numbered from 1 to 5, each include materials or objects whose characteristics are given in the following table.

Classification of explosible
materials or objects in
risk divisions

Class number	Division number	characteristics of materials or objects in the Division
1	1	Materials or objects essentially involving a danger of explosion in mass, i.e. affecting nearly the total charge practically instantaneously.
	2	Materials or objects involving a danger of projection but not a danger of explosion in mass.
	3	Materials or objects involving a danger of fire with minimal danger by blast and projection effects, but not exhibiting any danger of explosion in mass. This Division includes the following: Sub-Division 3a, consisting of materials or objects whose combustion gives rise to considerable heat radiation, Sub-Division 3b, consisting of materials or objects that burn fairly slowly, or of which some burn after the others, with minimal blast and projection effects.
	4	Materials or objects not involving very significant dangers, designed or packaged so as to exhibit a relatively minor danger, or whose effects, in case of firing or priming, do not give rise to the projection of fragments of appreciable dimensions, and remain, in all cases, sufficiently small to avoid significantly hindering fire-fighting operations and the application of emergency measures.

continued

Class number	Division number	characteristics of materials or objects in the Division
	5	Materials which are as dangerous as those of Division 1 if they explode, but which are relatively insensitive. These materials display a very low probability of priming and passage from combustion to detonation, unless they are found in large amounts in a confined space. They shall not explode under the external fire explosion test.

Article 5

The classification of explosible materials or objects in a risk division may depend on their packaging, and particularly on the type of packaging employed.

B COMPATIBILITY GROUPS

Article 6

Each of the compatibility groups is designated by a capital letter:
A, B, C, D, E, F, G, H, J or K.

Two other groups with special properties are added to them, designated L and S respectively.

The composition of these different groups is given in the following table.

Classification of explosible materials or objects in compatibility groups and possible classification codes

group designation	description of explosible materials or objects in the group	risk divisions 1.1	 1.2	 1.3	 1.4	 1.5
		classification codes				
A	Primary or priming explosive, i.e. material which, even in small quantities, detonates under the action of a flame, friction or slight impact.	1.1A				
B	Object containing primary explosive.	1.1B	1.2B		1.4B	
C	Secondary low explosive (with the exception of black powder) or propellant explosive or object containing such a material.	1.1C	1.2C	1.3C	1.4C	
D	Secondary high explosive, or object containing such an explosive without built-in priming devices and without propellant charges, or non-bulk black powder in closed packing acceptable for transport.	1.1D	1.2D		1.4D	1.5D
E	Object containing a secondary high explosive without built-in priming devices with propellant charges, with the exception of those containing an inflammable liquid (classified under J) and those which contain a hypergol liquid (classified under L).	1.1E	1.2E	1.3E	1.4E	

continued

group designation	description of explosible materials or objects in the group	risk divisions				
		1.1	1.2	1.3	1.4	1.5
		classification codes				
F	Object containing secondary high explosive with built-in priming devices and with or without propellant charges, with the exception of those containing an inflammable or hypergol liquid.	1.1F	1.2F	1.3F	1.4F	
G	Pyrotechnic composition or object containing such a composition or object containing, together with another explosible material, a lighting, incendiary, tear-inducing or smoke-producing composition, with the exception of any hydroactive object (classified under L) or one containing white phosphorus (classified under H) or one containing an inflammable liquid or gel (classified under J).	1.1G	1.2G	1.3G	1.4G	
H	Object containing both an explosible material and white phosphorus.		1.2H	1.3H		
J	Object containing both an explosible material and an inflammable liquid or gel.	1.1J	1.2J	1.3J		
K	Object containing both an explosible material and a toxic chemical.		1.2K	1.3K		

continued

group designation	description of explosible materials or objects in the group	risk divisions classification codes				
		1.1	1.2	1.3	1.4	1.5
L	Material or object which must be isolated from any other material or object of a different type, i.e. one which does not have the same properties or the same components. Black powder in bulk or in packing not acceptable for transport.	1.1L	1.2L	1.3L		
S	Material or object packed or designed in such a manner that all the effects due to accidental operation only exhibit a minor danger and remain within the packing or do not affect its immediate vicinity.				1.4S	

Article 7

Materials or objects in Groups A to H, J and K cannot be stored in the same depot if they belong to different compatibility groups. However, different groups of these materials or objects may be placed in a depot of the establishment if suitable measures are taken to avoid any transmission of a pyrotechnic accident between these different groups.

Materials or objects in Group L shall be separated if they are of different types, and shall not be placed together with materials or objects belonging to another group.

Materials or objects in Group S may be stored with materials or objects of all the other groups, with the exception of Groups A and L.

C CLASSIFICATION PROCEDURE

Article 8

The procedure for inclusion in Class 1 and classification in a risk division and, if applicable, in a compatibility group, involves a series of tests performed by:

- an organization approved by the Minister responsible for Industry,
- under the responsibility of the manufacturer, provided that the installations and methods employed for these tests have been inspected within the two previous years by an organization approved by the Minister responsible for Industry,
- a service appointed by the Ministry of Defence in the establishments under his jurisdiction.

This procedure is applicable to explosible materials or objects which are not classified or insufficiently known.

The final classification shall not be altered without justification. Such justification shall be provided by the safety analysis, which shall, in particular, take account of effective specific operating conditions.

SECTION 3 POTENTIAL RISKS

A DANGER ZONES

1 Classification of danger zones

Article 9

In each elementary pyrotechnic installation, i.e. in each work location situated outdoors or in a room, isolated or forming part of a workshop, depot or storeroom, and containing a charge of explosible materials or objects, this charge is at the source of danger zones broken down into the five categories indicated below, classified according to the probable gravity of the dangers which they incur for persons and property.

designation of zone	Z_1	Z_2	Z_3	Z_4	Z_5
foreseeable personal injury	mortal injury in more than 50% of cases	serious injuries which may be mortal	injuries	possibility of injuries	very low possibility of slight injuries
foreseeable property damage	very serious damage	serious damage	average and slight damage	slight damage	very slight damage

2 Area of danger zones

Article 10

The area of danger zones depends essentially on the land configuration, the protective systems installed, and on the type and, in particular, the risk division of the explosible materials or objects giving rise to the dangers.

Article 11

The distances R (expressed in metres), indicated in this Article, the limits of danger zones with a charge of mass Q (expressed in kilograms) of explosible materials or objects, placed at ground level, are defined in a normal atmosphere, i.e. in temperature and pressure conditions about 15 °C and 1013 millibars, above a flat ground without special protection.

Measures taken in the application of Article 2 of Law No.70-575 of 3 July 1970 may allow lower values of these distances if the safety of workers is not affected.

Article 11.1 Case of a charge of materials or objects of Division 1.1

designation of zone	Z_1	Z_2	Z_3	Z_4	Z_5
distance R from the charge of mass Q	$0 < R_1 \leq 5Q^{1/3}$	$< R_2 \leq 8Q^{1/3}$	$< R_3 \leq 15Q^{1/3}$	$< R_4 \leq 22Q^{1/3}$	$< R_5 \leq 44Q^{1/3}$

Any mass Q liable to detonate is the centre of the danger zones defined above, but, at any point where a detonation is liable to cause other detonations almost simultaneously, Q represents the sum of the masses liable to detonate almost simultaneously.

Detonations are said to be almost simultaneous if they follow each other sufficiently closely (at time intervals of a few milliseconds) to produce a peak overpressure at a point, which is greater than that of those that they would produce if they occurred separately.

It is assumed that, in flat land without special protection, the detonation of a mass Q:

- causes, within a radius $R = 0.5Q^{1/3}$,
- may cause, within a radius $R = 2.4Q^{1/3}$
  if there is a risk of projection,

the nearly simultaneous detonation of any mass liable to detonate.

Article 11.2 Case of a charge of materials or objects in Division 1.2

(a) $Q \geq 100$.

(b) $10 \leq Q < 100$: the distances shown in the table below may be reduced by one-third.

(c) $Q < 10$: the limits of danger zones shall be determined by a special study.

In cases (a), (b) and (c) examined above, Q represents the net mass of explosible materials, with the exception of containers.

If the materials or objects exhibit both a danger of explosion in mass and a major risk of projection (over 150 grams more than 15 metres), the danger zones to be considered are the largest of those which have been determined for these materials or objects considered as belonging to:

- Division 1.1,
- Division 1.2.

designation of zone	Z_1	Z_2	Z_3	Z_4	Z_5

(1) In case of munitions of calibre ≤ 60 mm or in case of the risk of projection of more than 150 grams over more than 15 metres, without the risk of projections of over 250 grams over more than 15 metres:

distance R from the charge of mass Q	$0 < R_1 \leq 15$	$< R_2 \leq 90$	$< R_3 \leq 200$	$< R_4 \leq 60 Q^{1/3}$ or 300 if $300 \geq 60 Q^{1/3}$	$< R_5 \leq 120 Q^{1/3}$ or 600 if $600 \geq 120 Q^{1/3}$

(2) In case of munitions of calibre > 60 mm or in case of the risk of projection of over 250 grams over more than 15 metres:

distance R from the charge of mass Q	$0 < R_1 \leq 25$	$< R_2 \leq 135$	$< R_3 \leq 300$	$< R_4 \leq 75 Q^{1/3}$ or 400 if $400 \geq 75 Q^{1/3}$	$< R_5 \leq 150 Q^{1/3}$ or 800 if $800 \geq 150 Q^{1/3}$

Article 11.3 **Case of a charge of materials or objects in Division 1.3**

designation of zone	Z_1	Z_2	Z_3	Z_4

(1) In case of materials or objects in Sub-Division 1.3a:

distance R from the charge of mass Q	$0 < R_1 \leq 2{,}5 Q^{1/3}$	$< R_2 \leq 3{,}3 Q^{1/3}$	$< R_3 \leq 5 Q^{1/3}$	$< R_4 \leq 6{,}5 Q^{1/3}$

(2) In case of materials or objects in Sub-Division 1.3b:

distance R from the charge of mass Q	$0 < R_1 \leq 1{,}5 Q^{1/3}$	$< R_2 \leq 2 Q^{1/3}$	$< R_3 \leq 2{,}5 Q^{1/3}$	$< R_4 \leq 3{,}25 Q^{1/3}$

This case does not include zone Z_5.

pyrotechnic accident shall be estimated and designated respectively by P_1, P_2, P_3, P_4 and P_5, according to whether the probability of such an accident is extremely rare, very rare, rare, fairly frequent or frequent.

C EVALUATION OF PYROTECHNIC RISKS

Article 14

Whenever specified, and especially in cases discussed in Article 3 of Decree No.79-846 of 28 September 1979 mentioned above, the safety analysis, accompanied by all valid justifications, determines the following for each elementary pyrotechnic installation.

(a) Classification of explosible materials or objects in the appropriate risk division or sub-division.

(b) The resulting danger zones, with due consideration, if applicable, of specific explosive properties of these materials or objects, and taking account of planned measures or prevailing conditions likely to reduce or to aggravate the danger, and in particular, the installation of protection systems such as earthworks, walls or shields.

(c) The estimated probability of a pyrotechnic accident and the measures taken to avoid the transmission of such an accident between elementary pyrotechnic installations, or even within such an installation, when it contains materials or objects of different compatibility groups.

SECTION 4 MAXIMUM ALLOWABLE RISKS IN DANGER ZONE

A INVENTORY OF INSTALLATIONS TO BE PROTECTED

Article 15

The table below defines the different categories of installations to be protected against the effects of a pyrotechnic accident liable to occur in an elementary pyrotechnic installation which, with its access roads and auxiliary structures which are indispensable in its immediate vicinity, is designated a_0.

Article 11.4 **Case of a charge of materials or objects in Division 1.4**

Designation of zone	Z_2	Z_3	Z_4
distance R from the charge of mass Q	$0 < R_2 \leq 0.3\,Q^{1/3}$ or 5 if $0.3\,Q^{1/3} > 5$	$< R_3 \leq 10$	$< R_4 \leq 25$

This case does not include zones Z_1 and Z_5.

Materials or objects of type 1.4S do not involve greater dangers than those of zones Z_4.

Article 11.5 **Case of a charge of materials in Division 1.5**

The danger zones are the same as those determined in the case of a charge of materials or objects in Division 1.1.

Article 12 .

In normal temperature and pressure conditions above flat land and without protection, the distances from the explosible charge which shall be taken as limits of zones Z_1, Z_2, Z_3, Z_4 and Z_5 are those indicated in Article 11 above, unless the specific explosive properties of the charge justify a different evaluation of the area of the danger zones defined in Article 9 above.

These distances shall be increased if specific conditions prevail which are liable to aggravate the danger.

They may be reduced if the land configuration or the installation of effective protection systems reduce the gravity of the danger.

B PROBABILITY OF A PYROTECHNIC ACCIDENT

Article 13

In each elementary pyrotechnic installation, depending on the types of explosible materials or objects which may be found therein, and the types of operation which are performed therein, the probability of a

type of installation	characteristics of each installation category	classi-fication symbol
(a) Structures or locations inside a pyrotechnic establishment.	(1) Pyrotechnic installations (work locations, workshops, depots, storerooms) and their access roads and auxiliary structures which are indispensable in the near vicinity of a_0.	a_1
	(2) Pyrotechnic installations not classified "a_1". Internal traffic lanes.	a_2
	(3) Non-pyrotechnic buildings and premises.	a_3
(b) Traffic lanes outside a pyrotechnic establishment.	(1) Slightly travelled lanes in which the traffic does not exceed 200 vehicles per day.	b_1
	(2) Travelled lanes in which the traffic ranges from 200 to 2000 vehicles per day.	b_2
	(3) Heavily travelled lanes in which the traffic is equal to or greater than 2000 vehicles per day.	b_3
(c) Structures or locations outside a pyrotechnic establishment.	(1) Uninhabited and infrequently visited structures (garden shelters, farm sheds etc).	c_1
	(2) Inhabited or visited premises related to the establishment or isolated dwellings.	c_2
	(3) Industrial, commercial or agricultural installations or inhabited or visited premises, which are not necessarily related to the establishment. Non-buried water supply and distribution installations, electric power supply and distribution installations such as high and medium voltage electric power networks, tanks and piping containing inflammable materials, air energy production and transmission units etc.	c_3

continued

type of installation	characteristics of each installation category	classi-fication symbol
(c) continued	(4) Gathering places of persons (playgrounds, religious gathering places, markets, school, hospitals etc), densely built-up areas, tall buildings and buildings forming a curtain wall.	c_4

B INSTALLATION LAYOUT REQUIREMENTS

Article 16

The table below gives the possible layout of the different categories of installation defined above in each danger zone characterized by:

(1) Subscript i of Z_i, indicating the gravity of the dangers incurred.

(2) Degree j of probability P_j of a pyrotechnic accident in the installation giving rise to it.

Probability of pyrotechnic accident

danger zone	P_1	P_2	P_3	P_4	P_5
Z_1	a_0	a_0	a_0 (*)	a_0 (**)	a_0 (**)
Z_2	a_1 a_2	a_1 a_2 (*)	a_1	a_1 (*)	a_1 (**)
Z_3	a_1 b_1 c_1 a_2 a_3	a_1 b_1 c_1 a_2	a_1 a_2	a_1	a_1 (*)
Z_4	a_1 b_1 c_1 a_2 b_2 c_2 a_3	a_1 b_1 c_1 a_2 b_2 c_2 a_3	a_1 b_1 c_1 a_2	a_1 a_2	a_1
Z_5	a_1 b_1 c_1 a_2 b_2 c_2 a_3 b_3 c_3	a_1 b_1 c_1 a_2 b_2 c_2 a_3 b_3 c_3	a_1 b_1 c_1 a_2 b_2 c_2 a_3 b_3 c_3	a_1 b_1 c_1 a_2 b_2 c_2 a_3 b_3 c_3	a_1 b_1 c_1 a_2 b_2 c_2 a_3 b_3

continued

NOTE

(*) Indicates that the personnel required to operate the installation concerned shall not be subjected for more than 10% of their working time to risks equivalent to those to which they are exposed in this installation.

(**) Indicates that no person shall be found in the zone and installation concerned, in application of the requirements of Article 27 of Decree No 79-846 of 28 September 1979.

The number of persons allowed to gather simultaneously in zones Z_1 and Z_2 shall be limited to the minimum.

The number of persons present simultaneously throughout installation a_0 exhibiting a probability of pyrotechnic accident greater than P_1 shall not normally exceed 5.

The installations a_0(*) located in Z_1P_3 and a_0(**) in Z_1P_4 may be changed respectively to a_0 and a_0(*) if it can be shown that, in these installations, perceptible signs occur providing advance warning of an accident or an explosion, such as abnormal smells or noises, excessive overheating, characteristic smoke etc, providing certain foreknowledge of the imminent occurrence of a pyrotechnic accident, but allowing the personnel in danger enough time to leave the exposed zone in complete safety.

Article 17

Any area common to two danger zones belongs to the zone in which the possibilities of installation are the least.

Article 18

The foregoing provisions constitute minimum requirements for worker safety, and do not waive the observation of any other regulation concerning the holding, transport, fabrication and use, storage, analysis and experimentation of explosible materials or objects, as well as their destruction and possible protection against electromagnetic radiation.

C INSTALLATION LAYOUT PLAN

Article 19

The limits of danger zones shall be noted on a drawing of the installation or pyrotechnic establishment concerned and of its surroundings.

This drawing, appended to the safety file, or broken down in the different safety analyses, indicates the layout of the different installations and, for each installation, the estimate of the probabilities of a pyrotechnic accident.

If necessary, this drawing shall include enlarged drawings of some parts of the establishment, in order to distinguish each of the work locations, workshops, depots and storerooms liable to be the source of a pyrotechnic accident.

Article 20

The Director of Regulations and Legal Matters of the Ministry of the Interior, the Director of Armaments and the Chiefs of Staff of the Army, Navy and Air Force at the Ministry of Defence, the Director of Prevention of Pollution at the Ministry of the Environment and Quality of Life, the Director of Labour Relations at the Ministry of Labour and Participation, the Director of Industrial Quality and Safety at the Ministry of Industry, the Director of Land Transport at the Ministry of Transport, are charged, each in his own area, with the enforcement of this Ministerial Order, which shall be published in the Journal Officiel of the French Republic.

Paris, 26 September 1980

The Minister of Labour and Participation,
for the Minister and by delegation:
D. Balmary . . . . The Director of Labour Relations

The Minister of the Interior,
for the Minister and by delegation:
C. Goudet . . . . The Director of Regulations and Legal Matters

The Minister of Defence,
for the Minister and by delegation:
J.C. Roqueplo . . . . The Director of Legal Matters

The Minister of the Environment and the Quality of Life,
for the Minister and by delegation:
T. Chambolle . . . . The Director of the Prevention of Pollution

The Minister of Industry,
for the Minister and by delegation:
F. Kosciusko-Morizet . . The Director of Industrial Quality and Safety

The Minister of Transport,
for the Minister and by delegation:
C. Collet . . . . The Director of Land Transport

GAP TESTS AND HOW THEY GROW

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Abstract

Available data from four different gap tests were compared. The study indicated a linear relation between the critical gap lengths (50% point) of the NOL LSGT and those of each of the other three tests, hence a linear relation for any pair of the 4 tests.

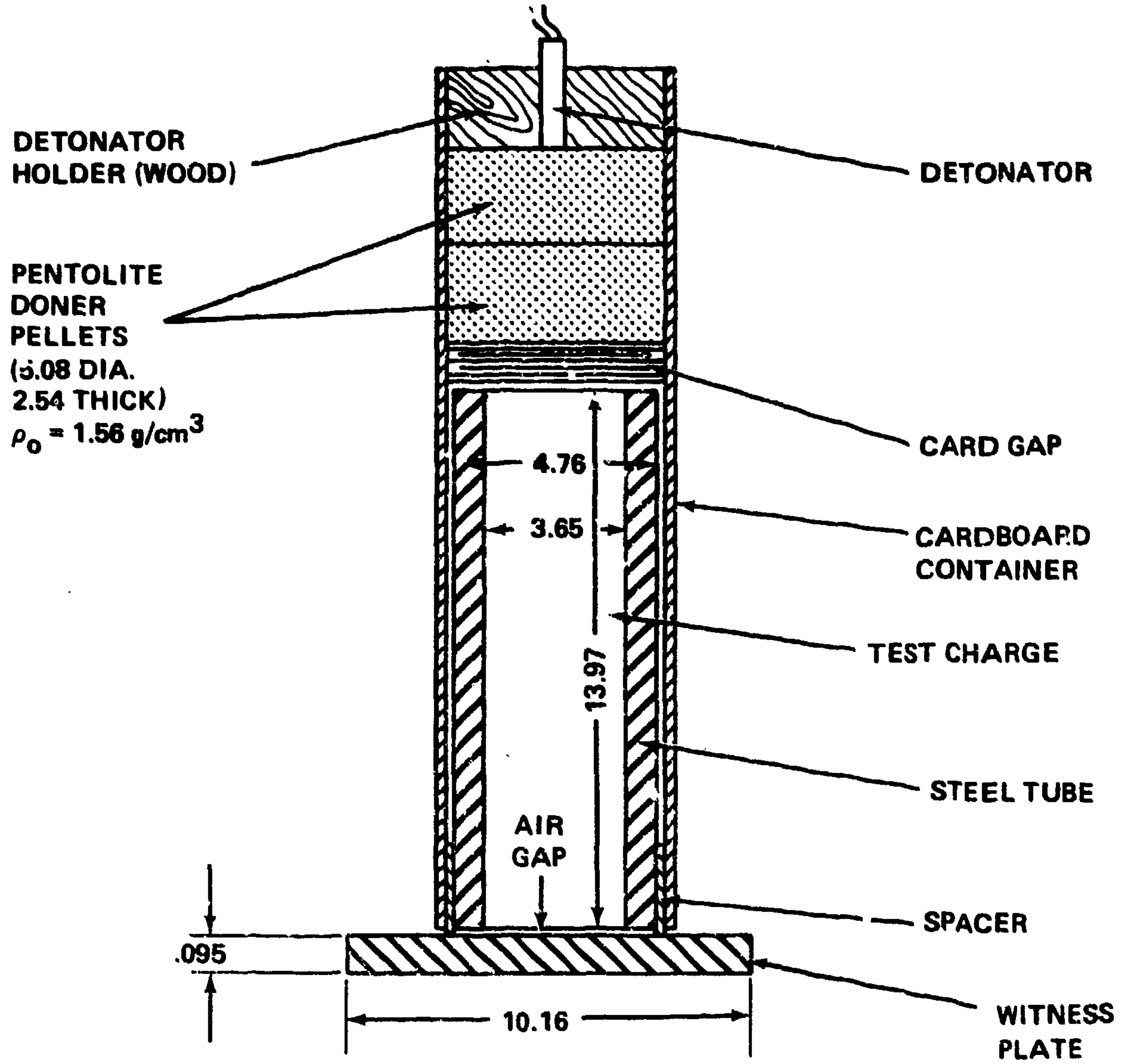
On the other hand, the approximate equivalency curve between the 50% gaps of the NOL LSGT and those of the recently developed expanded LSGT has been drawn with some curvature. The reasons for this are presented, and the detonation properties leading to increased size of the gap test are described. Finally, the recently developed "super" gap test is compared to the others and its objective considered.

For well over a quarter of a century, gap tests have been used to assess the relative shock sensitivity of explosives. A gap test consists of an explosive donor followed by a solid attenuator followed by an explosive acceptor, the test material. The attenuator thickness is varied until detonation occurs in 50% of the trials. This 50% point or critical thickness measures the relative shock sensitivity <u>in the particular test configuration</u>. The test may be confined or unconfined, calibrated or uncalibrated, witnessed by steel plate or pipe or other explosives. In fact, the test had no sooner been invented, than various experimenters started modifying it until now dozens of gap tests exist.

Recently, however, an additional complication has been introduced with the advent of a group of materials known as insensitive high explosives (IHE). Some of these cannot be initiated in the more conventional gap tests. Consequently, larger and larger gap tests have been designed to test IHE.

It is the objective of this paper to show that there are unexpected correlations between gap tests of very different designs, to show why testing of IHE leads to larger tests, and to discuss two recent large tests: the expanded large scale gap test (ELSGT) and the "super" gap test.

Since our largest data base is for the NOL large scale gap tests, that test is shown in Figure 1 where one can see the series: donor, gap, acceptor, common to all such tests. Table 1 tabulates the differences in design of the tests with which its results are to be compared. Test 1 is the NOL large scale gap test (LSGT); Test 2 is the same with slightly different diameter and aspect ratio and without the steel confinement. That is an important difference because confinement decreases the effective critical diameter. Another comparison will be with the LANL LSGT (Test 3); it is unconfined and also uses a different attenuator: Dural instead of polymethyl methacrylate (PMMA). The final comparison is between the NOL LSGT and a new test developed by Forbes and coworkers, the IHE gap test (Test 4). As you can see in the table, this latter test has a diameter about one third that of the former, and although the steel cylinder containing the acceptor is thinner than that of the large scale gap



DIMENSIONS IN CM

FIG. 1 CROSS SECTION OF GAP TEST ASSEMBLY FOR NOL LSGT

TABLE 1

GAP TESTS FOR WHICH RESULTS ARE COMPARED

Test	Title	Diameter or ID cm	Aspect Ratio ℓ/d	Attenuator	Confinement cm
1	NOL LSGT	3.65	3.83	PMMA	0.56 Thick Steel
2	Unconfined LSGT	3.81	3.67	PMMA	None
3	LANL LSGT	4.13	2.46	DURAL	None
4	IHE Gap Test	1.27	4.00	PMMA	0.318 Thick Steel 1.59 Thick PMMA

Witness is steel plate or block for each test.

TABLE 2

COMPARISON OF RESULTS FROM CONFINED UNCONFINED NOL LSGT

Material	ρ_o g/cm^2	50% Gap[1] Confined	50% Gap[1] Unconfined
		in. x 10^2	in. x 10^2
DINA-c	1.60	279	226
Comp B-c	1.70	201	143
TNT-c	1.61-2	135	73
Pentolite-c	1.67-8	273-301	255-266
RDX-p	1.64	323	285

test, its ratio wall thickness to ID, is 1.6 times greater. Table 2 and Figure 2 show the comparison between standard LSGT results and those from the non-standard, unconfined test. As Figure 2 shows, there is a definite correlation between the 50% gaps for the five explosives (4 cast and 1 pressed) that have been run in both tests. Table 3 and Figure 3 show a similar correlation between NOL LSGT values (L) and LANL LSGT (L') values for cast and plastic bonded HE despite the differences in test dimensions

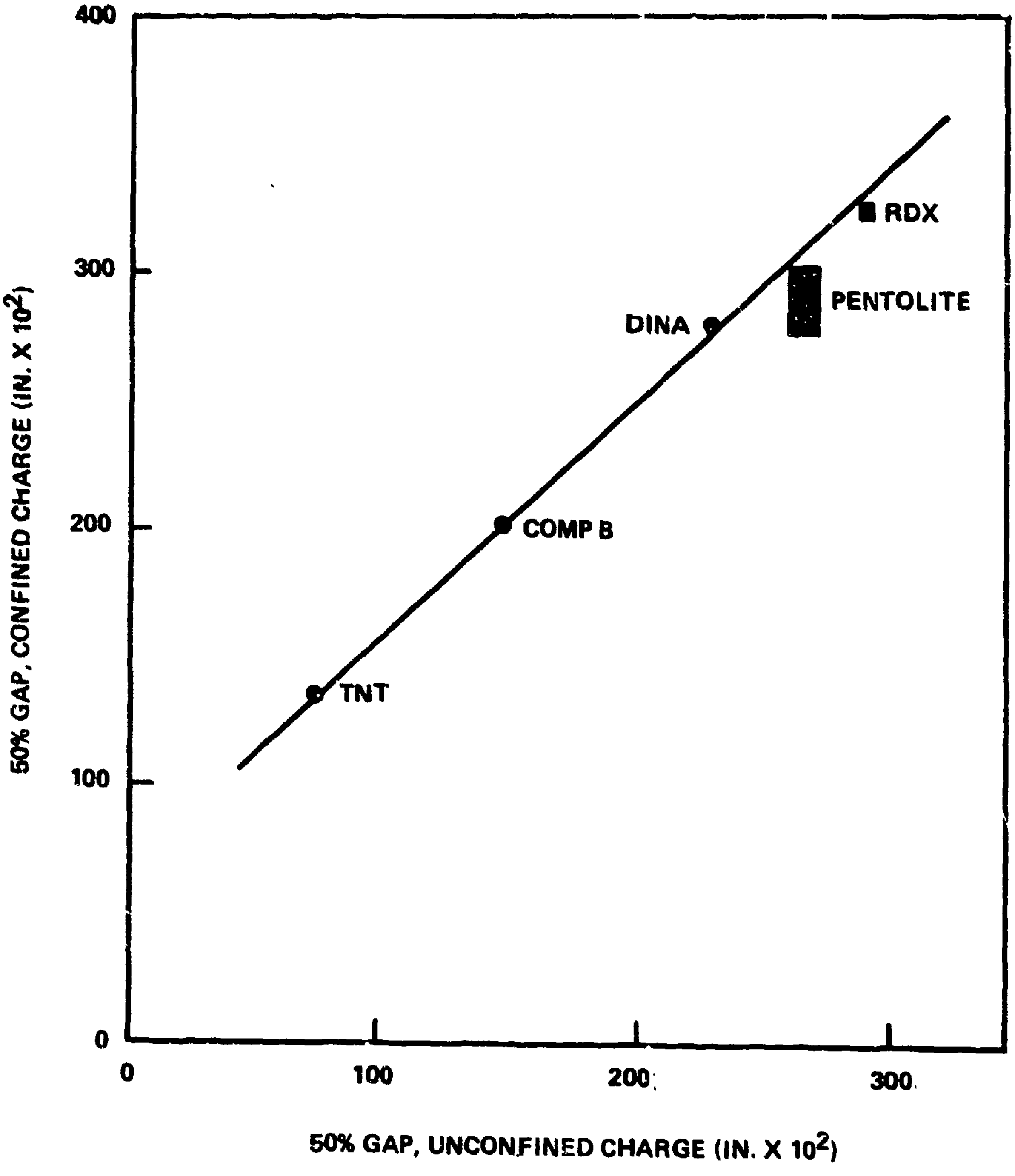


FIG. 2 COMPARISON OF RESULTS FOR CONFINED & UNCONFINED LSGT

TABLE 3
LSGT 50% GAP VALUES FOR
CAST AND PLASTIC BONDED HE

HE	ρ_0 g/cm^3	NOL LSGT[1] L, cards*	LANL LSGT[2] L', mm
Baratol-c	2.62-2.63	<123[a]	27.30[a]
Comp A-3	1.63	240	54.51
Comp B-c(A)	1.70-1.74	204.5	43.2
Comp B-3-c	1.70-1.72	213	50.3
Cyclotol-c 75/25	1.74-1.76	186	44.3
Octol-c 75/25	1.81-1.83	>217[b]	47.32
Pentolite-c	1.70	273	64.74
TNT-c	1.62	129	28.30
PBX-9404	1.85-1.87	238[b]	55.86

[a] $Ba(NO_3)_2$ content 27% and 24% at NSWC and LANL, respectively.

[b] ρ_0 = 1.78 g/cm^3.

*All values corrected to current pentolite donor.

and shock attenuator. (There is no similar correlation for pressed explosives, possibly because of differences in preparing pressed charges at different laboratories).

Table 4 and Figure 4 show the linear correlation between the IHE gap test and the NOL LSGT values for the three explosives that have been run in both tests. Evidently, the IHE gap test covers the same shock sensitivity range as the NOL LSGT, but with only 4.4% the amount of test explosive. Proper test design - in this case, choice of test dimensions and confinement, can reduce the amount of explosive needed for relative shock sensitivity testing. This brings us to a related question: what is the need for larger tests?

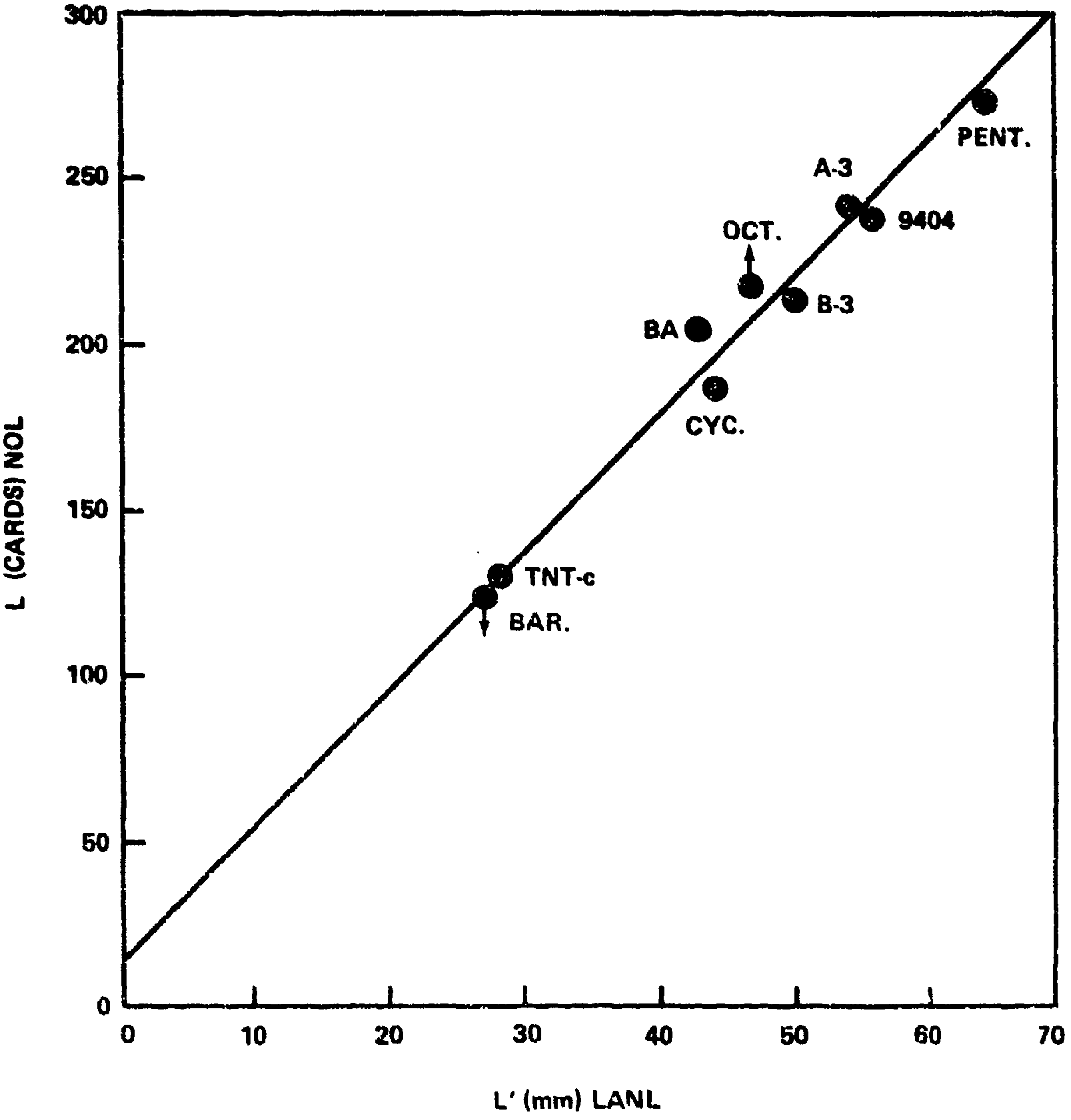


FIG. 3. COMPARISION OF NOL VS LANL LSGT VALUES

TABLE 4

COMPARISON OF NOL LSGT RESULTS WITH THOSE OF THE IHE GAP TEST

	ρ_o g/cm^3	IHE^3 50% Gap in.	LSGT' in. x 10^2
TATB	1.83	0.92	78-84*
TNT-c	1.61	1.30	124-135
TNT-p	1.57	1.92	193-198

*Higher value from G. T. West,"Classification of Explosives," Apr-June, 1976. Pantex Plant MHSMP-7630K.

To illustrate this problem, Figure 5 shows two fictitious curves of required 50% gap pressure (P_g) vs. charge diameter for two HE, A and B. Moreover, $2d_c(A) = d_c(B)$; d_c, the critical diameter, is that diameter below which propagation of steady-state detonation is impossible. My drawing leaves much to be desired, but it does show that initiation is impossible until $d \geq d_c$ and that the curve is very steep at diameters just slightly greater than d_c. That is why gap tests are only valid for $d \geq 3d_c$ so that the very steep portion of the curve is never used in a comparison. For example, if we use the results at $3d_c(A) = 1.5d_c(B)$ for both HE, we get a ΔP_g value much greater than if we use a diameter of $6d_c(A)$, i.e., both explosives are at $d \geq 3d_c$. The smaller difference is far more representative of the infinite diameter value. In other words, there is an infinite diameter value of gap sensitivity just as there is an infinite diameter value of detonation velocity D_∞. In both cases, the values measured near d_c are very different from the ideal or infinite diameter values.

The use of P_g as a relative shock sensitivity measurement is an approximation of course. In the first place, it approximates P_i, the actual initiating pressure transmitted to the explosive. Secondly, it omits the effect of the pressure-time history of the shock. But whatever criterion may be used to estimate initiation conditions: P, $P^n\tau$*, or mass velocity u, pressure is the dominant variable.

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*τ is approximate duration.

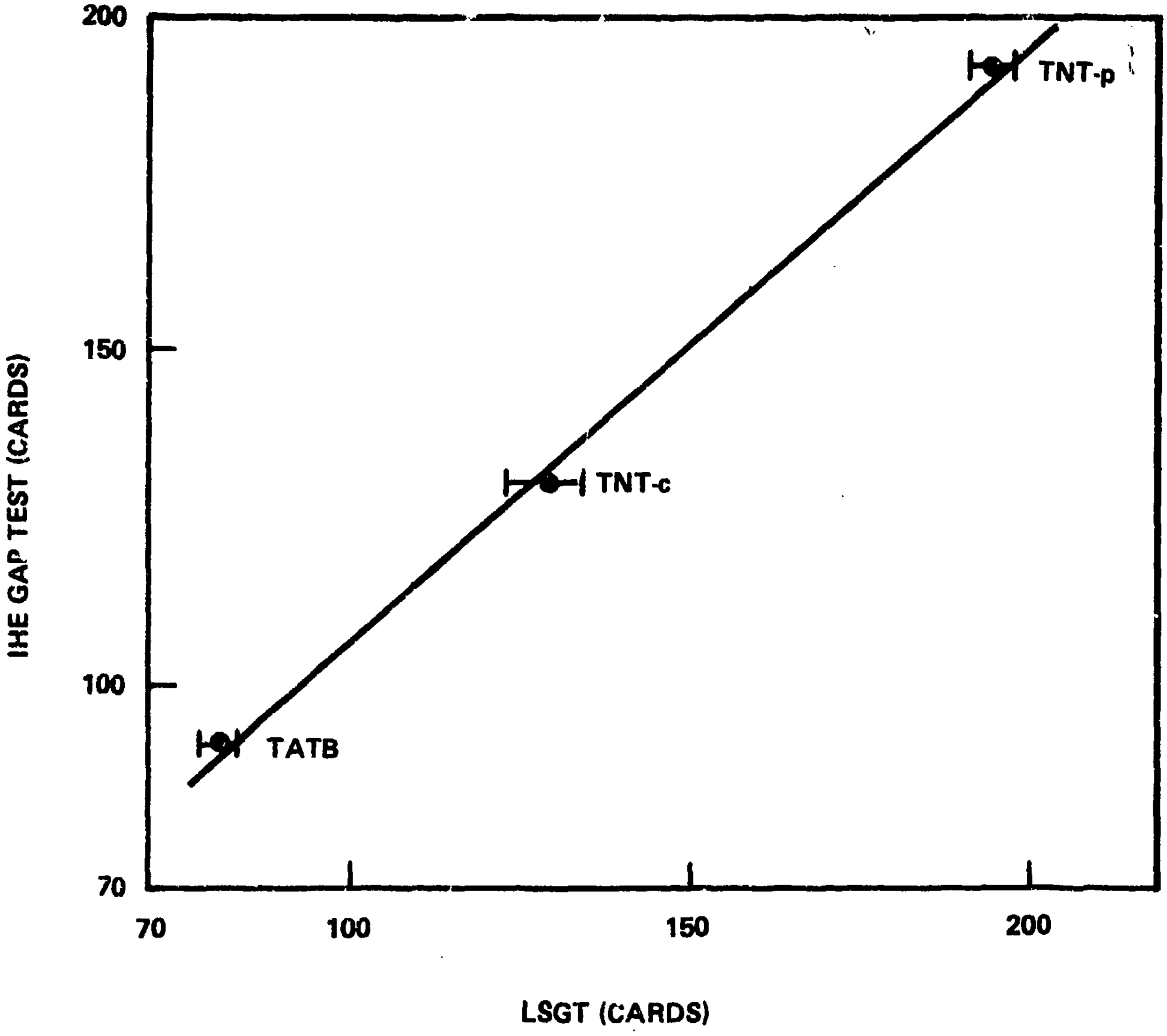

FIG. 4 COMPARISON OF RESULTS FROM LSGT AND IHE GAP

It follows from the illustration of Figure 5 that the demand for larger diameter gap tests is to allow HE of large d_c to be tested at $d \geq 3d_c$. Here d_c refers to effective critical diameter not to the d_c we measure on unconfined charges. Hence, we may decrease the effective d_c by confining the charge as well as by increasing the test charge diameter. With the objective of testing IHE in the proper diameter range, DDESB asked the Center (NSWC/WO) to design a larger test than the standardized NOL LSGT. We designed a gap test for which the acceptor and its confinement were scaled up by a factor of 2. Howevever, because of the manufacturer's available molds, the donor was scaled by only a factor of 1.875. Results from this test, the expanded LSGT, were reported at the March meeting of the JANNAF Working Committee on Hazards.[4] Figure 6 shows the two assemblies that were compared and Figure 7 gives the approximate equivalency curve found for the two tests.

You will note: (1) we have not drawn a straight line as in the other 3 correlations I have shown and (2) within experimental error, we could have drawn a straight line. As was pointed out in the original paper, the uppermost and lowermost points are not as well established as the two mid-points. Until this is done, we shall regard this approximate curve as more general than a straight line.

The scaling up of the NOL LSGT by a factor of two is about the practical limit of increasing the test size. As it was, the witness plates were scaled in thickness but not in length x width because they were then too heavy to handle. Nevertheless, there is a much larger gap test developed at Eglin AFB and reported at the previous DDESB Symposium and also at the 8th Symposium (International) on Detonation last year. This test, called the "super" gap test[5], is compared to the NOL LSGT in Figure 8 where both configurations are drawn to scale. This emphasizes the jump in magnitude of the dimensions.

Table 5 lists the results of the "super" gap test and those of the corresponding NOL LSGT. The latter value for tritonal was listed incorrectly in Reference 5. The 50% "super" gap values were obtained from the text of Reference 5 but the computed pressures (P_g) were taken from a chart displayed at the 8th Detonation Symposium. Reference 5 contains a

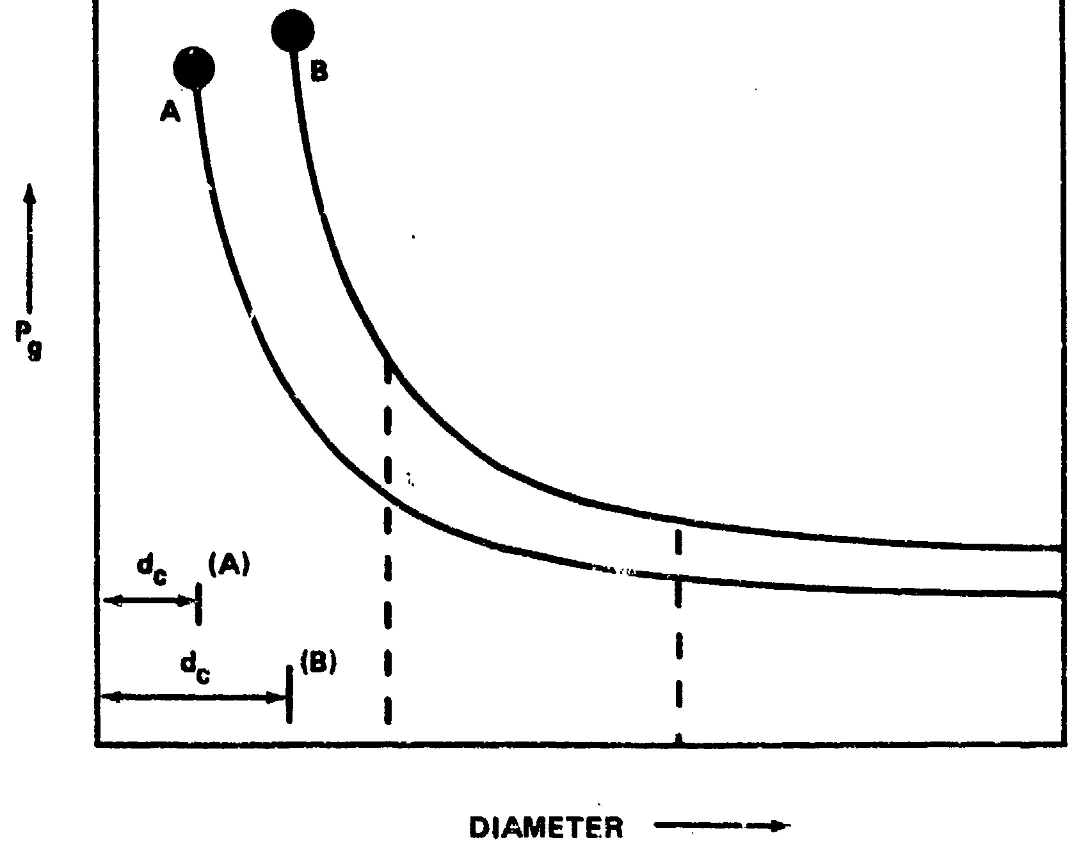

FIG. 5. P_g VS CHARGE DIAMETER FOR EXPLOSIVES A AND B

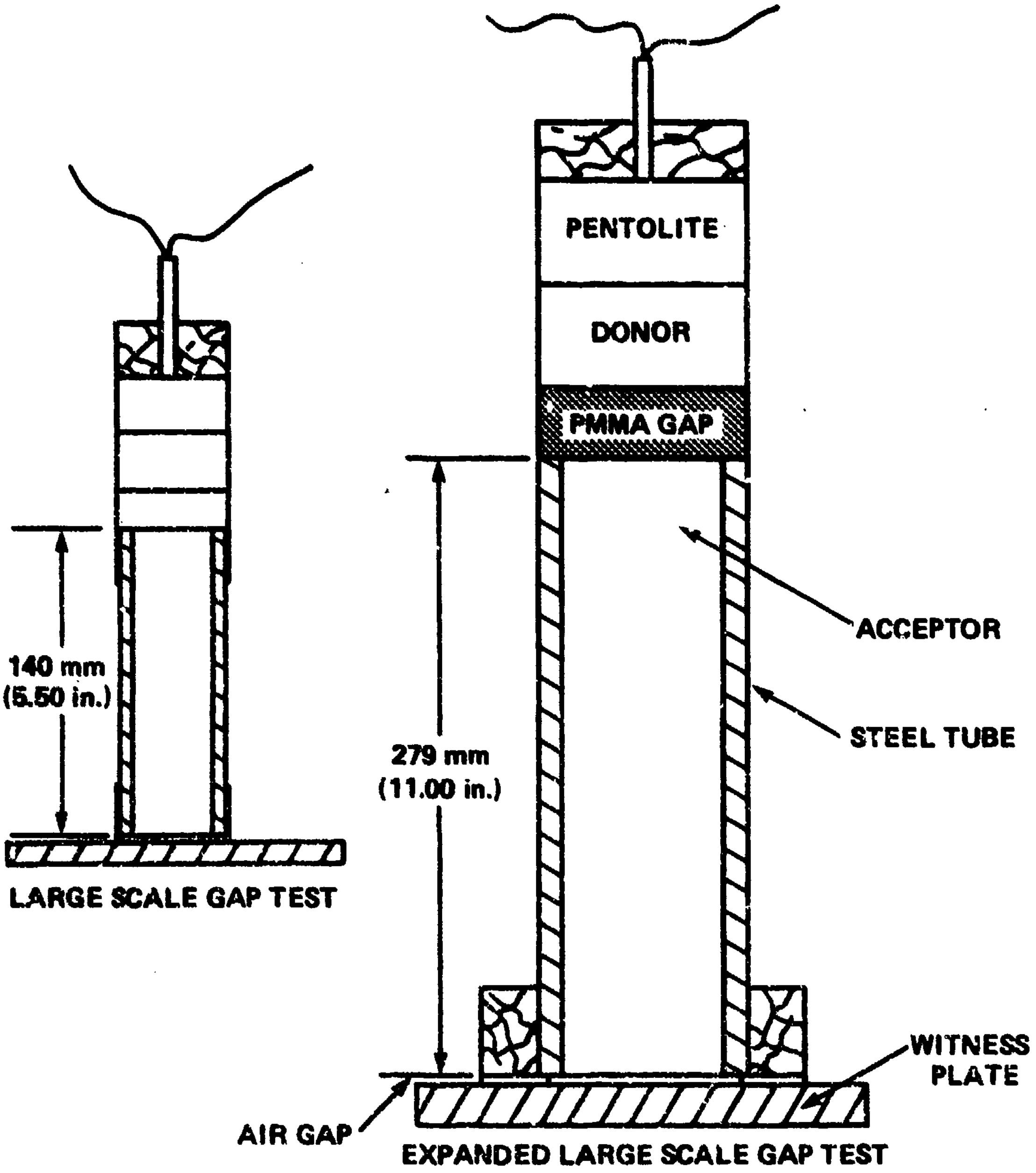

FIG. 6. COMPARISON OF LSGT AND ELSGT ASSEMBLIES

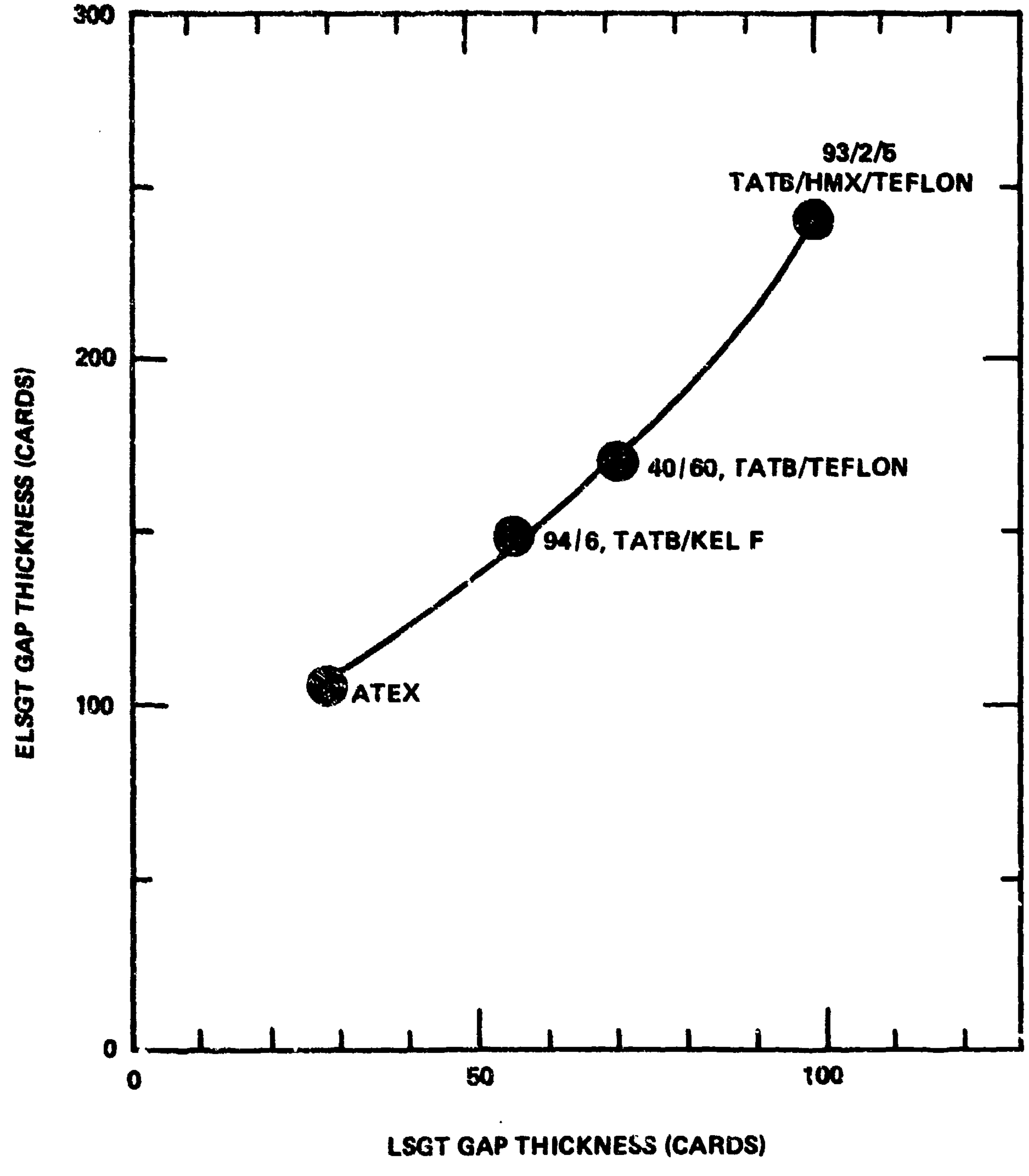

FIG. 7. THE ELSGT 50% GAP THICKNESS VERSUS THE LSGT THICKNESS

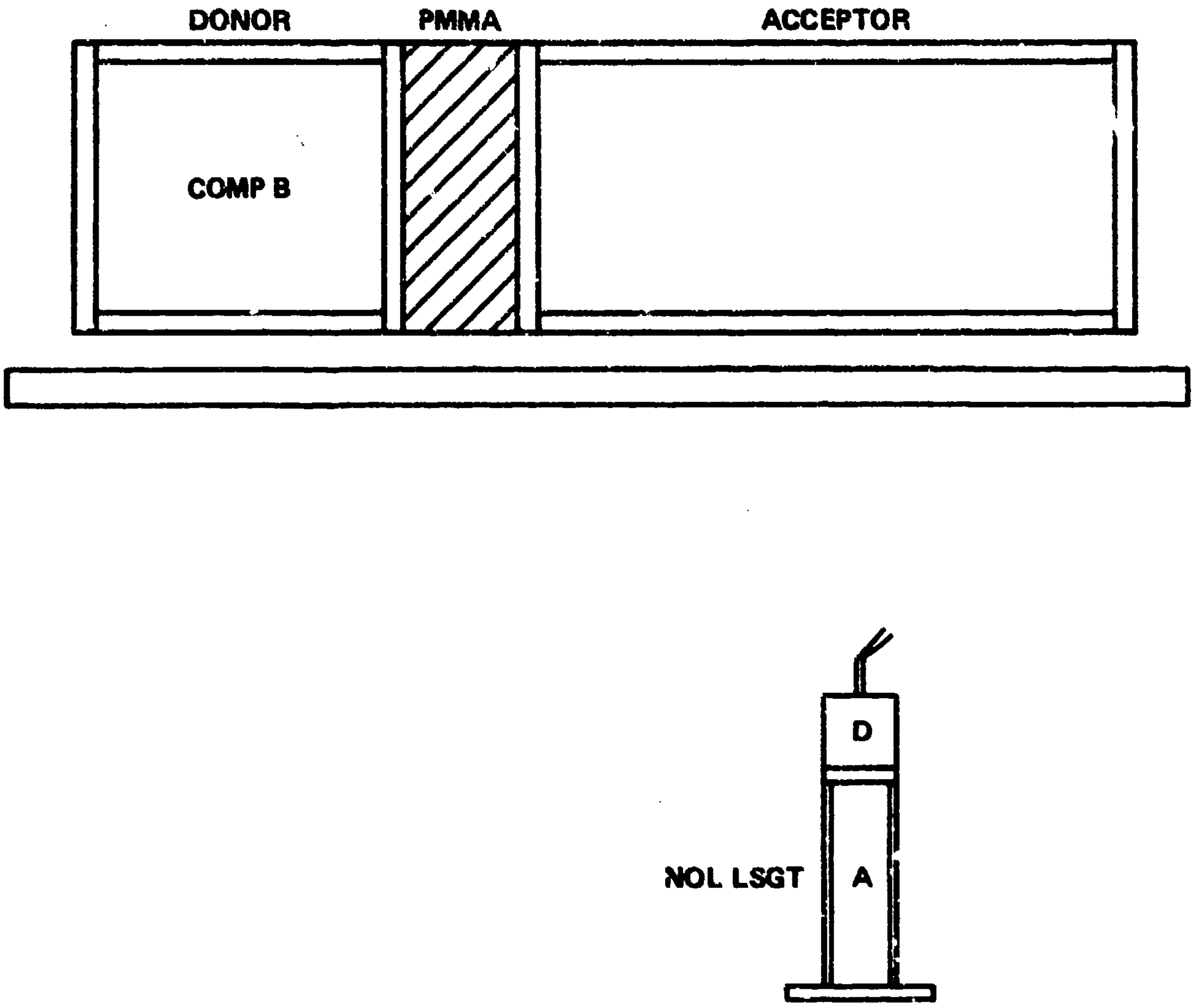

FIG. 8. COMPARISON OF "SUPER" GAP TEST WITH NOL LSGT.

TABLE 5

COMPARISON OF VALUES FROM "SUPER" GAP TEST WITH THOSE OF LSGT

Cast HE	ρ_o g/cm^3	"Super" Gap 50% Point[a] in.	"Super" Gap P_g[b] kbar	NOL LSGT 50% Point in.	NOL LSGT P_g kbar
Comp B	1.69	7* - 8	12	2.01-2.07	19.7-18.5
Tritonal 80/20	1.73	5 - 6	15	1.00-1.01	55
TNT/Wax 95/5	1.69	5* - 6	16	Not Tested	
TNT/NQ/Wax 60/35/5	1.61	2* - 3	40	Failed	

a. Values found in text of Ref. 5; values with asterisk closer to 50% gap value.

b. Values read from chart displayed at 8th Detonation Symposium

calibration curve (Reference 5, Figure 13) of P_g vs PMMA thickness. However, this curve gives no values for $P_g < 30$ kbar, but Figure 10 seems to extend the computed values to the pressures transmitted from the PMMA through the 0.5 in. steel confining the acceptor charge.

Not only is the scale of the "super" gap test much greater than that of the more widely used tests, but its purpose is also different. It is to "screen for an explosive's propensity to detonate or react violently as a result of shock induced sympathetic detonation of large ordnance such as general purpose bombs" (100 - 1000 kg HE). The more common gap tests are concerned with relative shock sensitivity, an explosive property. Some industrial laboratories classify their tests as property tests or use tests; in the present gathering, we call the latter vulnerability tests. Such tests are carried out when the available basic information is insufficient to permit a reliable prediction by any set of computations. This is essentially the case for the "super" gap test; I consider it a good field test for its specific purpose. Having said that, I will add that use of field tests will continue to demand large charges, but not necessarily many shots.

By way of summary, we have found that three pairs of gap tests of very different design give the same relative shock sensitivity ratings for a number of explosives. The number of data points were 3 - 9, too few, of course, to generalize. But in view of the differences in ratings I have seen from tests coming out of different laboratories, I should not have expected the linear correlations we saw. Despite these, Liddiard and I drew the approximate equivalence curve between the NOL LSGT and the ELSGT as non-linear because it is more general than the straight line and so must stand until better data are available. Finally, anything larger than the ELSGT should be considered a use or field test designed to address a specific problem rather than a test for general application.

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HIGH VELOCITY IMPACT SENSITIVITY OF COMMERCIAL SLURRY AND EMULSION EXPLOSIVES

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ABSTRACT

The phenomenon of high velocity impact initiation of commercial explosives was modelled numerically by means of a reactive hydrodynamic code in conjunction with the Forest fire model. Coefficients for the Forest fire model were determined from the Pop plots resulting from a series of wedge tests for each explosive investigated. Data for the reactive hydrodynamic code include the HOM equation of state parameters and Hugoniots.

Predicted results for projectile impact were compared with the experimental results obtained for the same explosive compositions. For a given projectile the agreement between the predicted values of impact velocity beyond which detonation would occur and the observed experimental values was good.

INTRODUCTION

Safety is a major concern in the area of commercial explosives. From the beginning of their development effort was directed towards the manufacture of safer products. However sensitivity is poorly understood and poorly defined. High velocity projectiles can be used to assess the impact sensitivity of commercial products. At the same time numerical techniques can be used to improve the understanding of the transition from impact to detonation.

Many models have been introduced to describe the initiation of heterogeneous explosives. The first attempts of modelling were made by Eyring(1) who developed his grain burning laws. Later Cook and Pauer(2) modified Eyring's theory to model the burning in liquid explosives containing bubbles. Mader(3) used Arrhenius kinetics and finite difference techniques to study the interaction of shock waves with density discontinuities.

The previous models although able to demonstrate the concept of the hot spots, were unable to model the initiation of practical explosives. To this end several attempts have been made. Such attempts are:

(a) The p^2t criterion by Walker and Wasley(4). According to this criterion a certain critical energy per unit area is necessary for the shock initiation to lead to detonation.

(b) The ignition and growth model by Lee and Tarver(5). This model is based on the Wilkins equation of state and the following equation for the reaction rate:

$$\frac{\partial F}{\partial t} = I\,(1 - F)^x n^r + G(1 - F)^x F^y P^z$$

$$\text{with } n = \frac{V_o}{V_1 - 1}$$

where F is the fraction of the explosive that has reacted. t is the time and V_o is the initial specific volume of the explosive, V_1 is the specific volume of the shocked unreacted explosive, P is the pressure and I, x, r, G, y and z are constants. These parameters are however unknown for most explosives and the technique to obtain them is not readily available.

(c) Feng and Hanaski(11) developed a hydrodynamic model using an equation of state proposed by Tait. Later, Feng et al(12) improved the model by using a different equation of state to describe the temperature of air bubbles contained in liquid explosives under dynamic loading. It was proposed that the Forest Fire Model(13) should be used to describe the decomposition rate of the explosive as a function of pressure.

(d) The Forest Fire model(6) which was developed by Charles Forest of the Los Alamos Laboratories. The Forest Fire technique describes the decomposition rate of the explosive as a function of the experimentally measured distance of run to detonation vs. shock pressure (Pop plot) and the reactive and unreactive Hugoniot. It is based on the single curve buildup principle and it has been used with success for the modelling of the behaviour of military high explosives.

Data for the model are the Pop plot, the Hugoniot of the explosive and the HOM equation of state parameters. This approach was adopted in this study as it was the most promising.

The Forest Fire model was selected to provide the decomposition rate as a function of pressure for the case of commercial slurry and emulsion products. The reaction rate vs. pressure relationship was used in our hydrodynamic model "HYDREL" to predict the initiation or failure of the explosive due to impact.

EXPERIMENTAL

In order to obtain Pop Plots and Hugoniot relationships for commercial explosives wedge tests were conducted. The wedge tests are named for the wedge shaped explosive which is shocked by a plane wave generator - booster - attenuator system. The explosive is wedge shaped so that the shock or detonation moving through it is visible through the slant face.

The slant face is usually covered with glass microballoons. Moreover the slant surface of the wedge is covered by a very thin plexiglas sheet so as to create a narrow gap between the explosives and the plexiglas. When the microballoons and air gap are compressed suddenly they flash brightly. A streak camera is set up with the slit parallel to the base of the wedge. The experimental technique is shown in Figure 1. A typical streak record from a wedge experiment is shown in Figure 2.

The shock which enters the wedge must have a high degree of planarity so that the point at which the shock wave becomes a detonation wave can be located. Moreover the planarity of the wave which impacts the wedge affects the measurement of the shock velocities before and after the detonation. For those reasons the shock which impacts the wedge must be produced by an accurate plane wave generator.

The system consists of a 12.7 cm plane wave generator, a pentolite (50% RDX, 50% TNT) booster, a plexiglas attentuator of various thickness and an explosive wedge. The wedge is placed at the centre of the attenuator plate in order to avoid edge effects which will affect the planarity of the wave at the sides.

The experimental results were analyzed by using the reflected Hugoniot technique.

The resulting Pop Plots are presented in Figures 3 - 7. Emulsions A and B are #8 blasting cap sensitive products containing 3% and 5% Aluminum. Emulsion C is a large diameter non cap sensitive product containing no aluminum. Slurries A

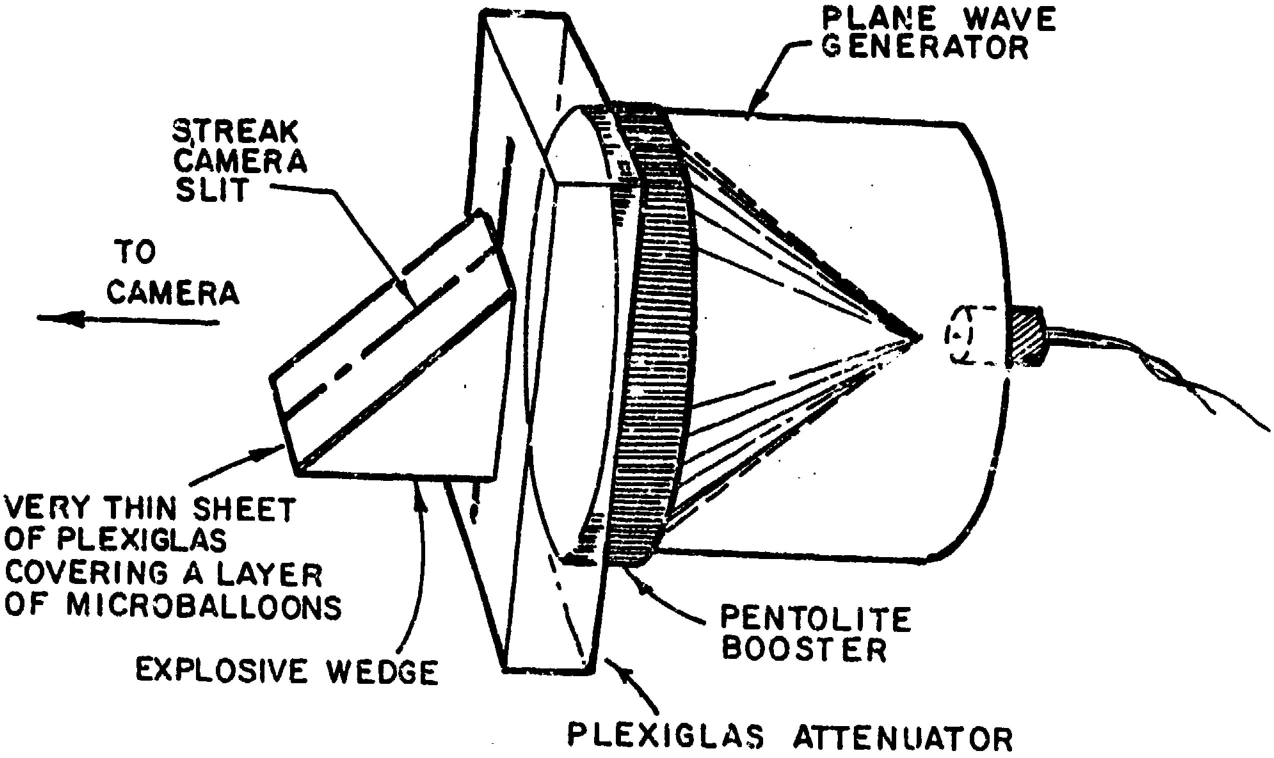

FIGURE 1: EXPERIMENTAL SET UP FOR WEDGE TESTS

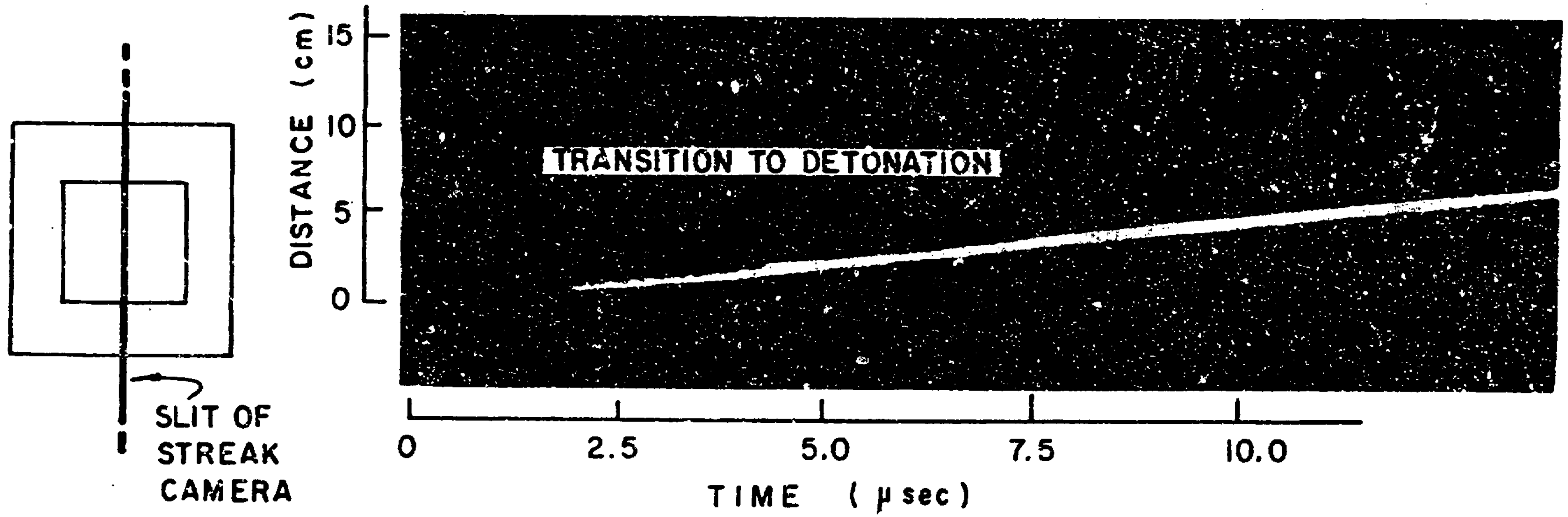

FIGURE 2: TYPICAL STREAK CAMERA RECORD

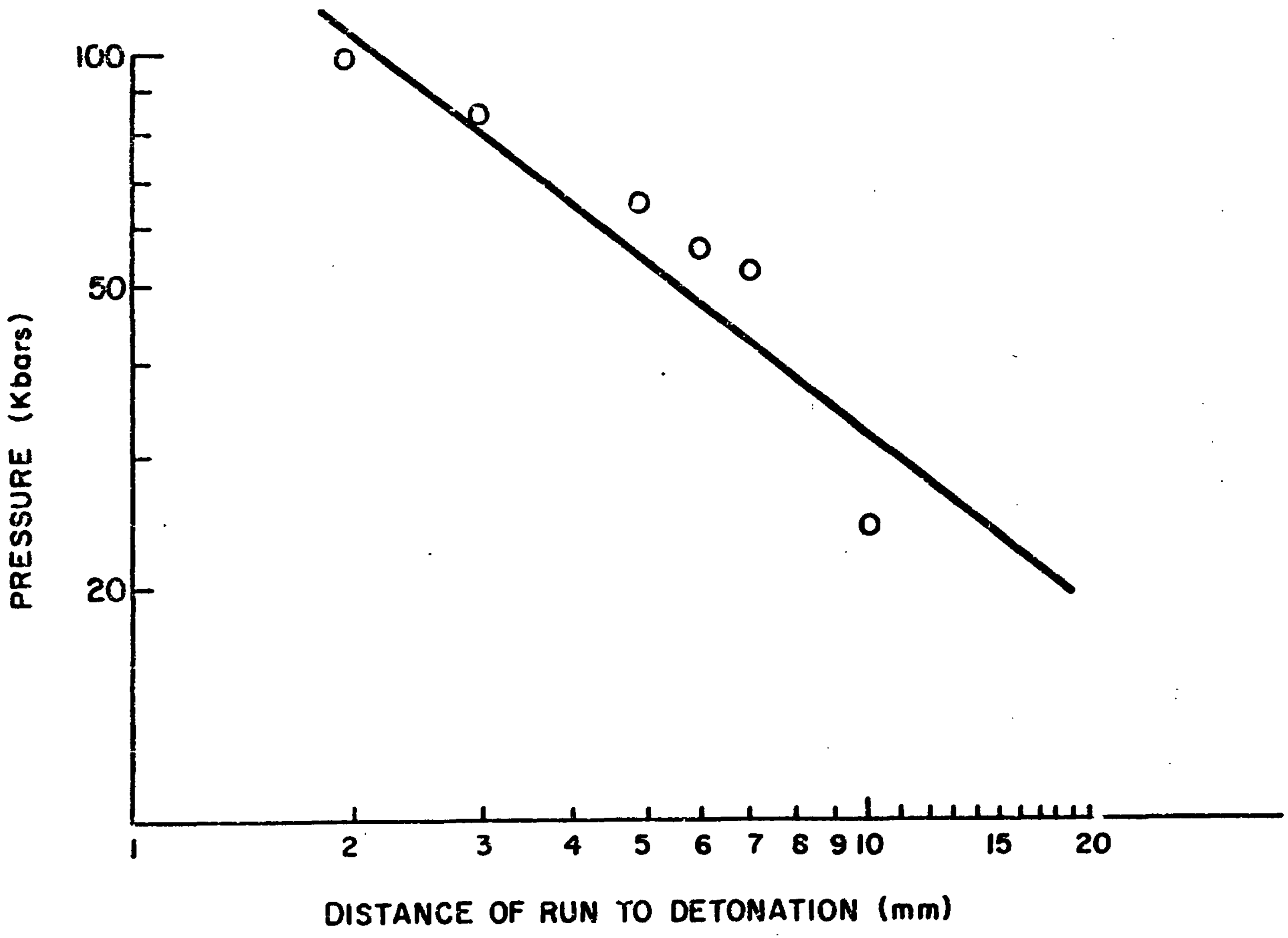

FIGURE 3: POP PLOT FOR EMULSION A

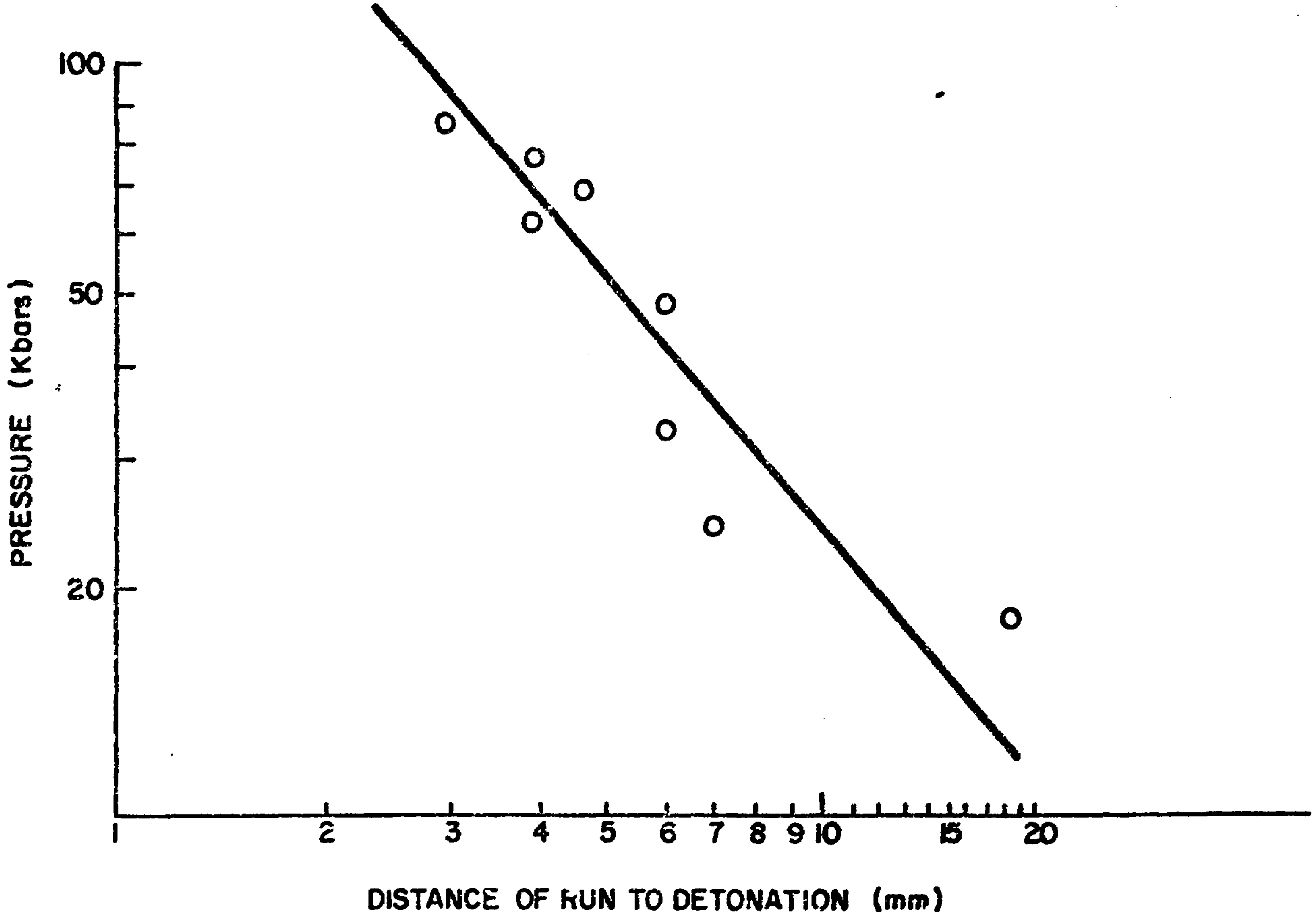

FIGURE 4: POP PLOT FOR EMULSION B

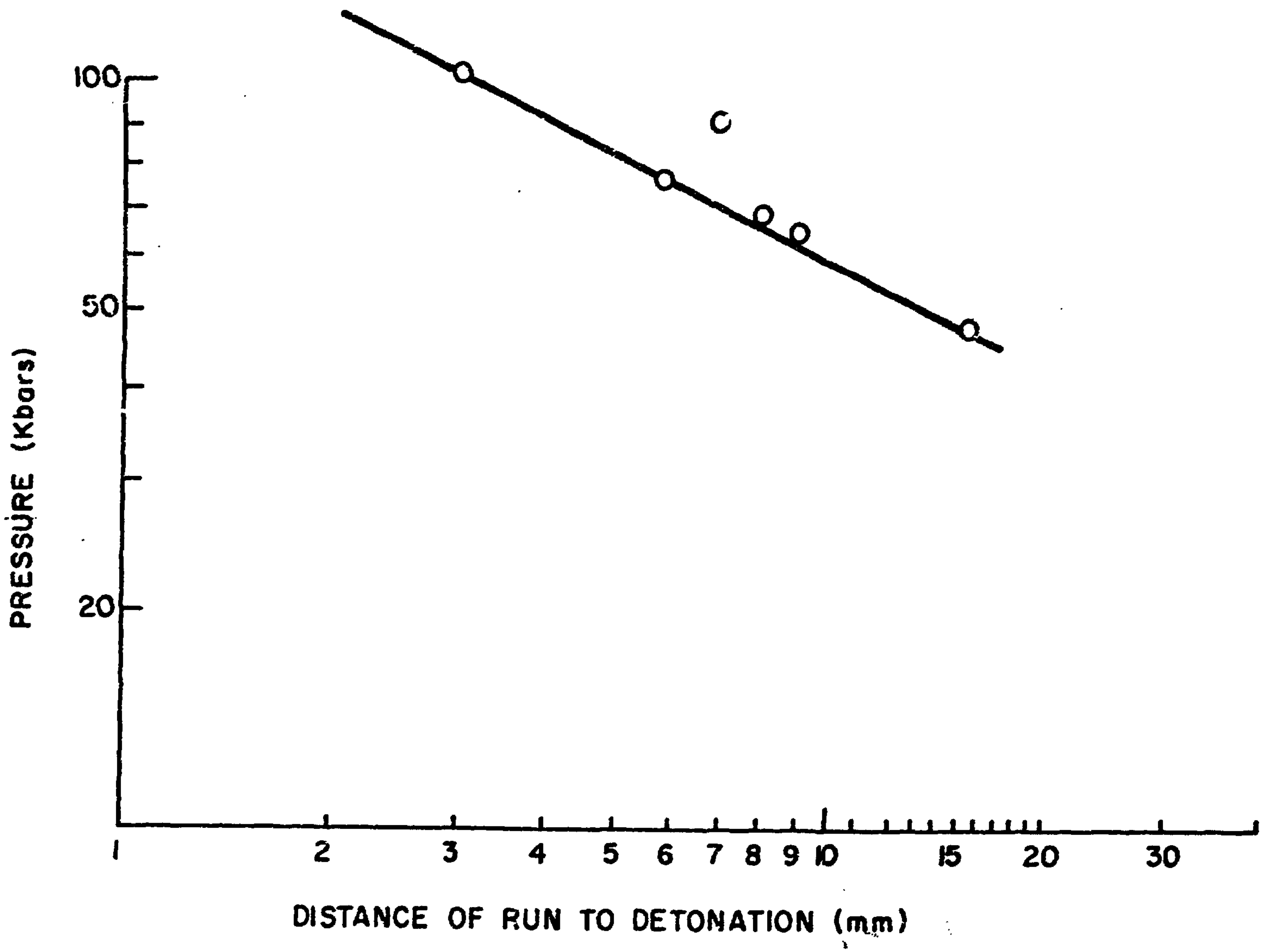

FIGURE 5: POP PLOT FOR EMULSION C

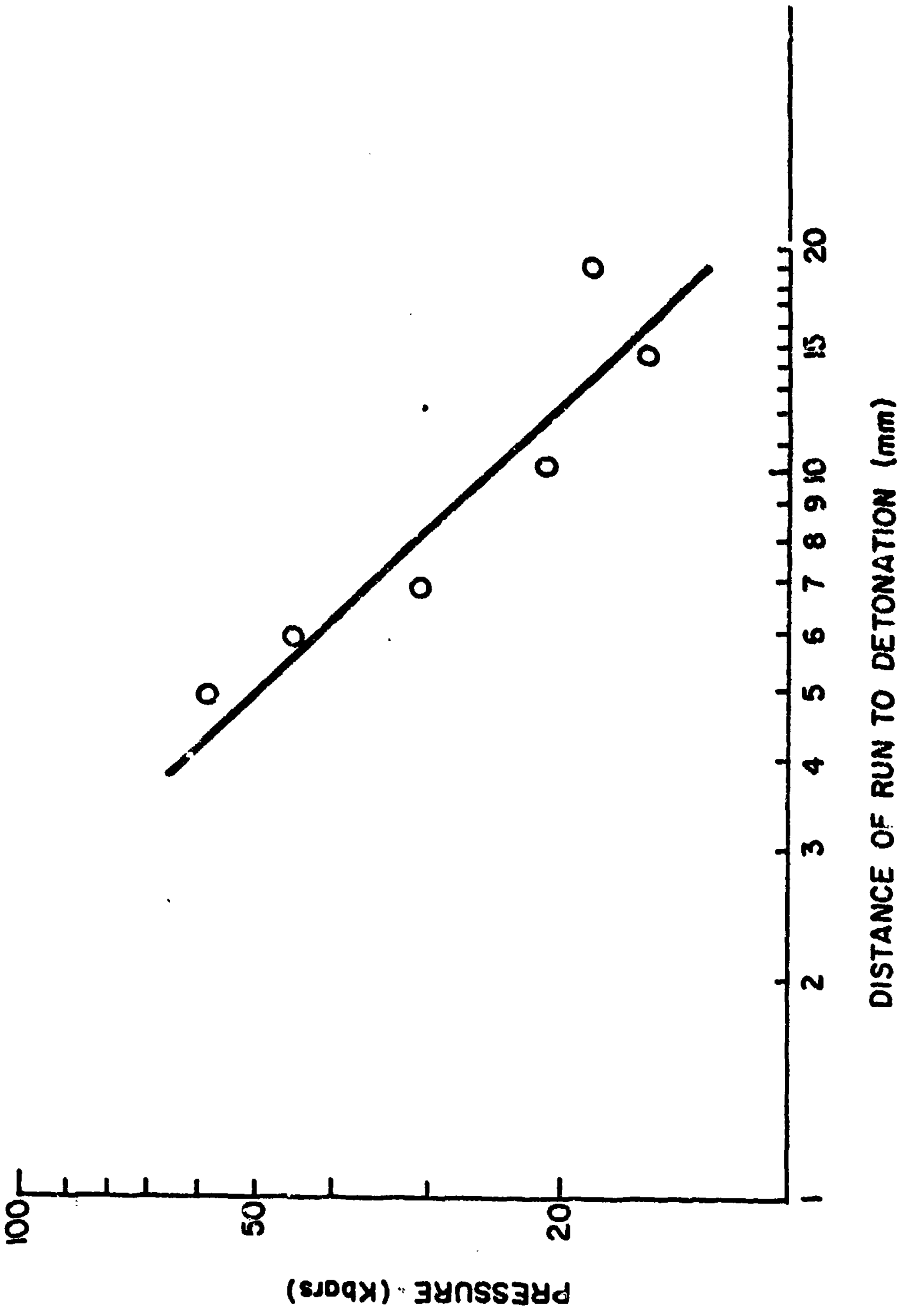

FIGURE 6: POP PLOT FOR SLURRY A

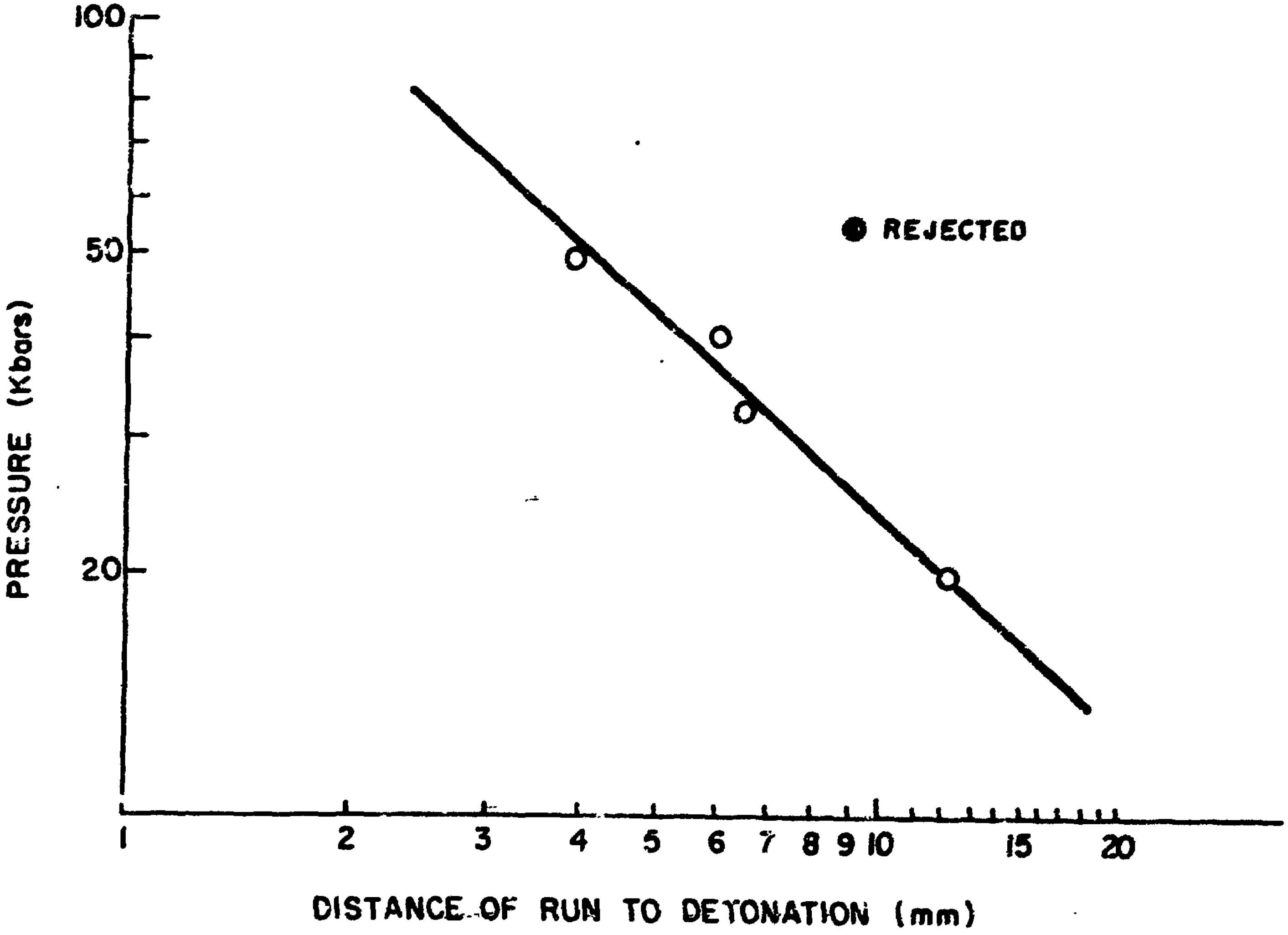

FIGURE 7: POP PLOT FOR SLURRY B

and B are small diameter #8 blasting cap sensitive aluminized products.

In order to examine the impact sensitivity of the explosives experimentally the following three techniques were used.

a. Large Projectile Impact Test

In this type of test aluminum projectiles were fired from a cannon towards an explosive target. A series of tests was conducted by varying projectile velocity and diameter. The projectile diameters were 2.5 cm, 5.1 cm, 10.2 cm and 15.2 cm. Usually the explosives were tested unconfined. However in some cases the explosives were confined in order to evaluate the effect of confinement. Confinement was achieved by placing the explosive in schedule 40 steel pipes. The projectile velocity was calculated by reading the time interval for passage of the projectile between two light sensors placed a known distance apart in front of the target.

The experimental set up is shown in Figure 8. The impact was observed by a HYCAM high speed framing camera having a writing speed of 3000 frames per second. Thus the detonation or failure can be determined by the review of the film. The result can also be characterized by the deformation of the projectile after impact.

Moreover the result can be characterized by the remains of the target explosive. In case of a detonation no remains of the target explosive are found.

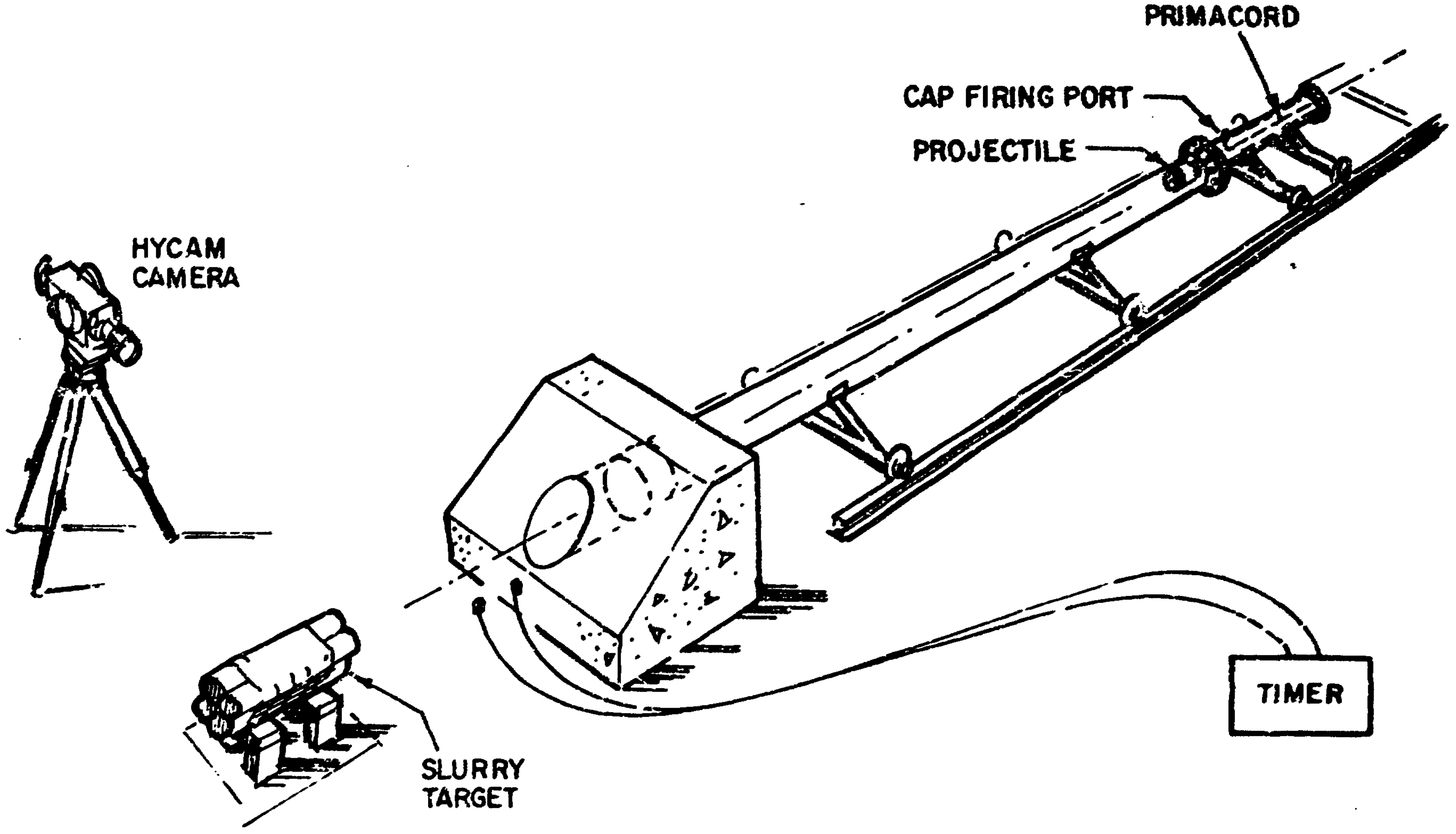

FIGURE 8: EXPERIMENTAL SET UP FOR THE LARGE PROJECTILE IMPACT TEST

The results of the cannon tests are presented in Table 1.

b. High Velocity Small Projectile Tests

For the case of the #8 cap sensitive emulsion explosives small projectiles were used. Small projectiels can travel fast enough to initiate most of the commercial products. The projectiles were made of brass and had a diameter and length of 13 mm. The experimental layout is shown in Figure 9. The velocity of the projectile is measured by using photocells. The results of the tests are shown in Table 2.

c. Flyer Plate Impact Tests

For the cap insensitive emulsion a flyer plate test was designed. The flyer plate can be more effective than metal projectiles for the following reasons:

1. It can obtain higher terminal velocities. Therefore it can produce shock pulses of higher amplitude in the explosive target. According to the p^2t criterion for the impact initiation of explosives the amplitude of the shock pulse is more important than its duration.
2. The flyer plate introduces essentially a one dimensional pulse when impacting the material. This diminishes the action of side release waves which can quench the detonation.

The flyer plates were made of aluminum and were driven by detonation waves at tangential incidence. The experimental set up is shown in Figure 10. The velocity of the plate is calculated by using the Richter equation:

EXPLOSIVE	PROJECTILE DIAMETER X LENGTH (cm)	PROJECTILE VELOCITY (m/s)	RESULT
SLURRY A	2.5 x 5.0	431	FAILED
	2.5 x 5.0	435	FAILED
		447	DETONATED
		454	DETONATED
SLURRY A	5 x 10	146	FAILED
		152	DETONATED
		194	DETONATED
		208	DETONATED
		239	DETONATED
SLURRY B	2.5 x 5.0	286	FAILED
		347	FAILED
		444	DETONATED
		537	DETONATED
SLURRY B CONFINED	2.5 x 5.0	277	FAILED
		286	FAILED
		337	DETONATED
		356	DETONATED
		363	DETONATED
SLURRY B	5 x 10	344	FAILED
		347	FAILED
		347	DETONATED
		350	DETONATED
SLURRY B	10 x 13	337	FAILED
		344	FAILED
		350	DETONATED
	15 x 15	219	FAILED
		344	DETONATED
		363	DETONATED

TABLE 1: PROJECTILE IMPACT TEST RESULTS FOR SLURRIES.

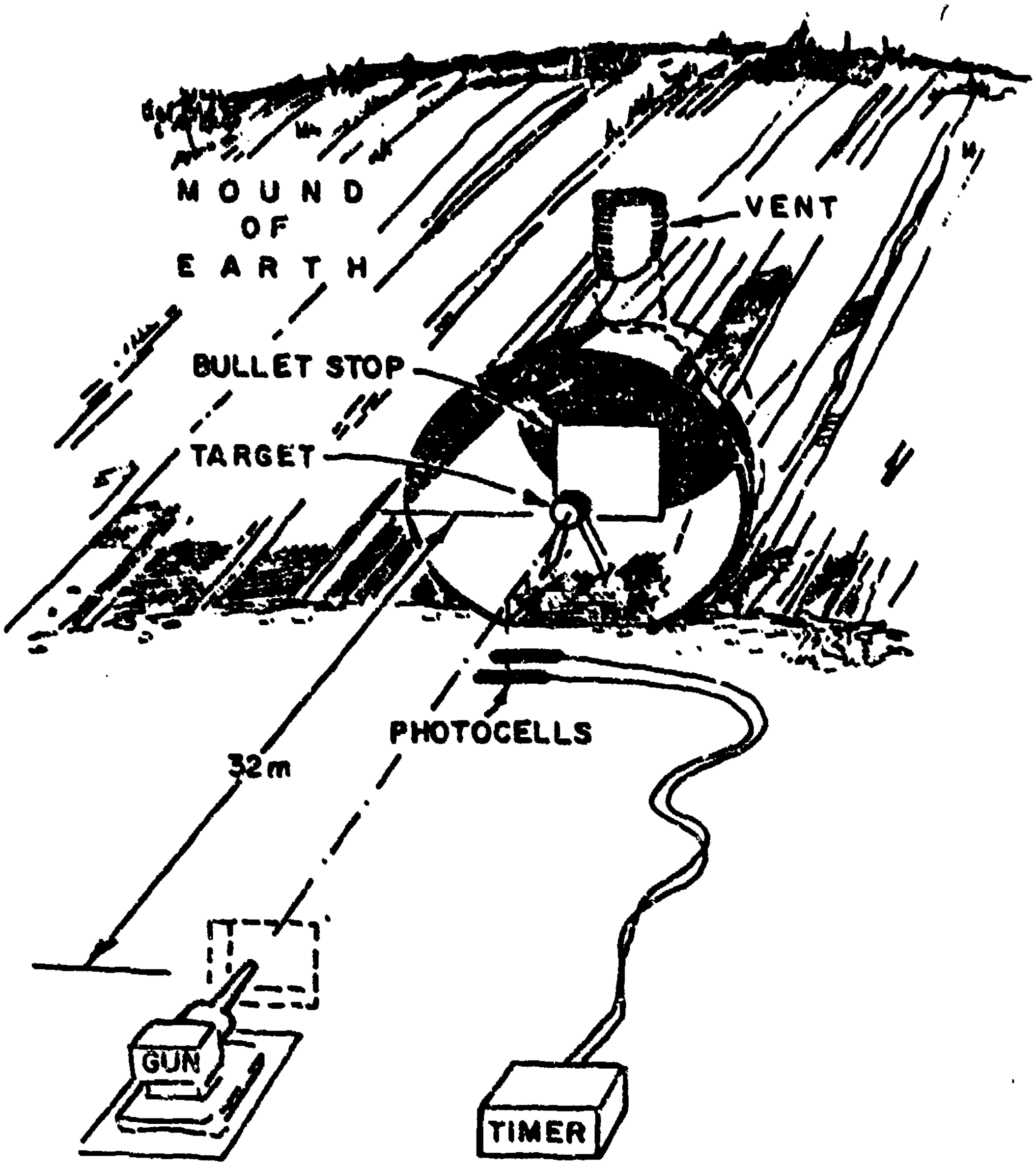

FIGURE 9: EXPERIMENTAL SET UP FOR THE HIGH VELOCITY SMALL PROJECTILE IMPACT

EXPLOSIVE	PROJECTILE VELOCITY (m/s)	RESULT
EMULSION A	856	DETONATED
	757	DETONATED
	745	DETONATED
	711	FAILED
	707	FAILED
	674	FAILED
	663	FAILED
EMULSION B	858	DETONATED
	830	DETONATED
	802	FAILED
	800	FAILED
	752	FAILED
	649	FAILED
EMULSION C	1067	FAILED
	1283	FAILED
	1316	FAILED

TABLE 2: RESULTS OF THE SMALL PROJECTILE IMPACT TESTS.

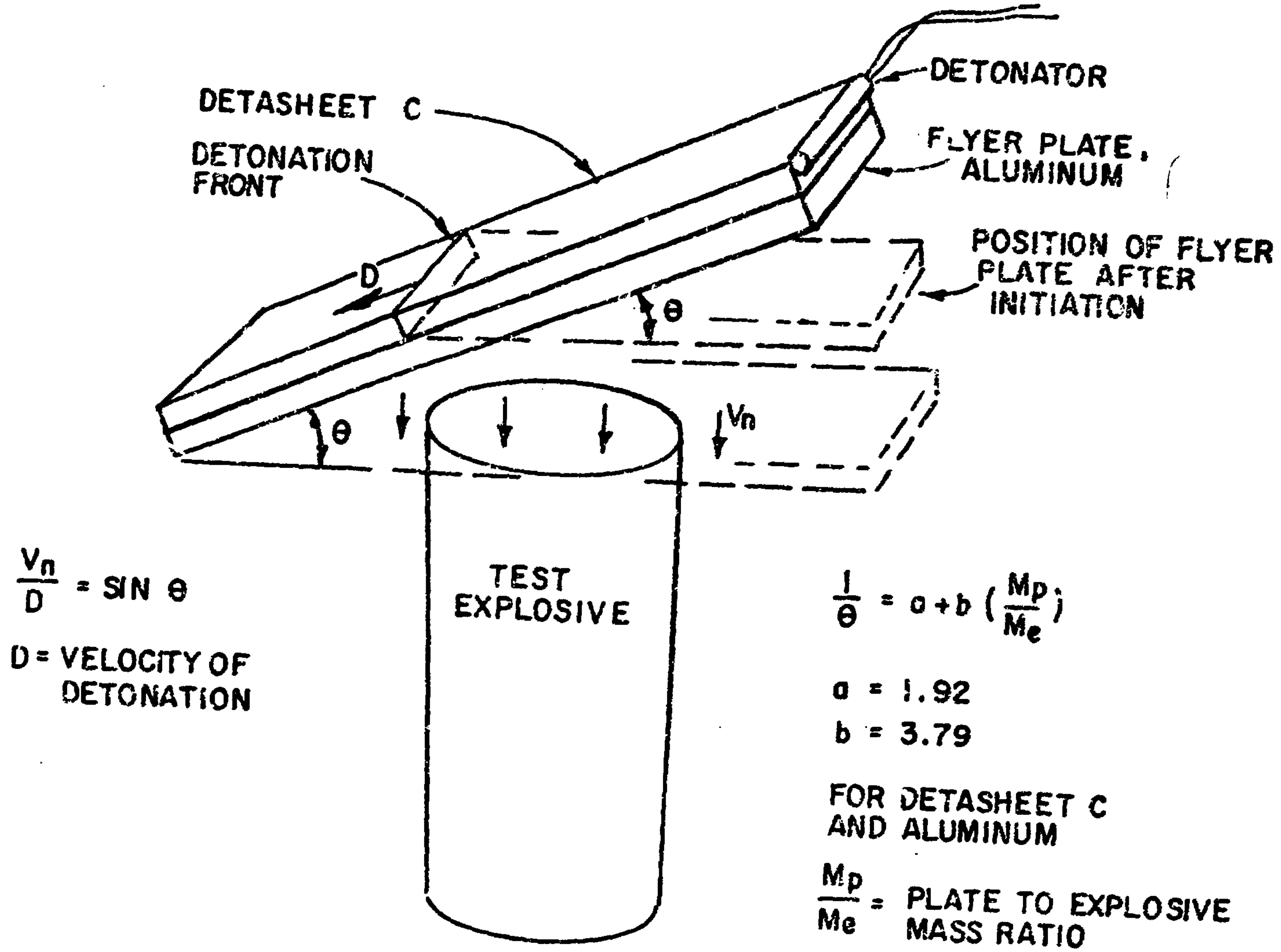
DETONATOR
DETASHEET C
FLYER PLATE, ALUMINUM
DETONATION FRONT
POSITION OF FLYER PLATE AFTER INITIATION
D
θ
θ
V_n
TEST EXPLOSIVE
$\frac{V_n}{D} = \sin\theta$
D = VELOCITY OF DETONATION
$\frac{1}{\theta} = a + b\left(\frac{M_p}{M_e}\right)$
$a = 1.92$
$b = 3.79$
FOR DETASHEET C AND ALUMINUM
$\frac{M_p}{M_e}$ = PLATE TO EXPLOSIVE MASS RATIO

FIGURE 10: METHOD OF PROJECTING FLYER PLATE

$$\frac{1}{\theta} = a + b\,(Mp/Me)$$

where θ is the turn angle (rads) a, b are constants determined for a given explosive metal plate combination and Mp/Me is the mass of the plate to mass of the explosive ratio.

The constants a, b in the above equation for the system aluminum metal plate driven by a plastic explosive called Detasheet C have been determined by Belanger and Matte(7) by using flash x-ray techniques. According to them a and b are 1.42 and 3.79 respectively.

The results of the flyer plate impact tests are shown in Table 3.

THE REACTIVE HYDRODYNAMIC MODEL

The hydrodynamic model "HYDREL" is a two dimensional finite difference Lagrangian code. For the calculations the material is divided into small cells by means of a grid. A typical grid describing the impact of a flyer plate on an explosive target is shown in Figure 11. The computations proceed by stepping forward in time in small increments. At each increment (cycle) stress, velocity, displacements and energies are calculated at each cell and coordinate point. For the reactive part the Forest Fire technique is normally used. However other types of burn are available such as the Arrhenius burn and the sharp shock burn. A simplified flow

ALUMINUM PLATE THICKNESS (mm)	LAYERS DETASHEET (number)	TURN ANGLE OF PLATE DETERMINED BY RICHTER EQUATION (degrees)	MP/ME WEIGHT RATIO	CALCULATED PLATE VELOCITY (m/s)	(ft/s)	RESULT	DIAMETER OF CHARGE (mm)
3.2	1	10.2	.98	1230	4020	FAILED	75
3.2	2	15.1	.49	1820	5960	DETONATED	75
9.5	5	13.8	.59	1660	5450	DETONATED	75

TABLE 3: FLYER PLATE IMPACT RESULTS FOR EMULSION C.

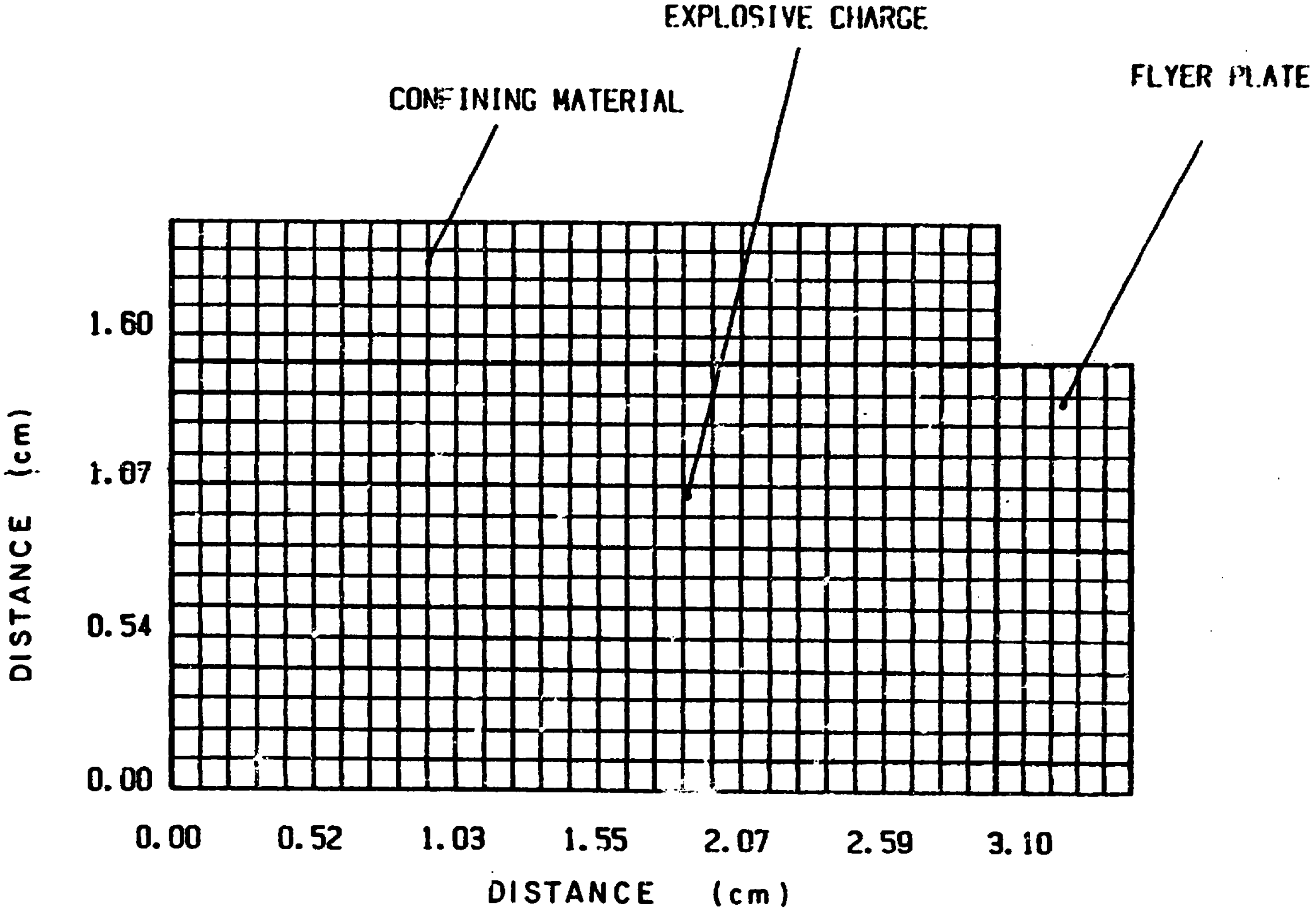

FIGURE 11: TYPICAL GRID FOR THE HYDRODYNAMIC MODEL "HYDREL"

chart of the program is given in Figure 12.

The Forest Fire rate is programmed as a function of pressure. The logarithm of the rate is expressed as:

$$\ln(\text{rate}) = A_1 + A_2 P + .. + A_n P^{n-1}$$

The logarithm of the rate is fitted to the pressure by the above equation for different pressure ranges in order to minimize the error by approximation. By adopting only one fit the technique might fail especially in the low pressure range. Moreover the rate is set to zero if the pressure is less than the minimum pressure in the fit. The burning is completed once the pressure reaches or is greater than the C-J pressure.

The equation of state used in the program is the HOM equation of state. For the explosive HOM has two parts; one for unreacted material and one for reaction products. For the inert materials HOM uses only the part for unreacted materials. HOM calculates the pressure and temperature given the internal energy, the specific volume and the fraction of the unreacted material. The HOM parameters for the unreacted explosive were measured (Hugoniot, density) and the parameters for the detonation products were calculated by using the TIGER code. In the calculation the C-J point was found and then the products were allowed to expand isentropically.

RESULTS

The predictions of the hydrodynamic code "HYDREL" were

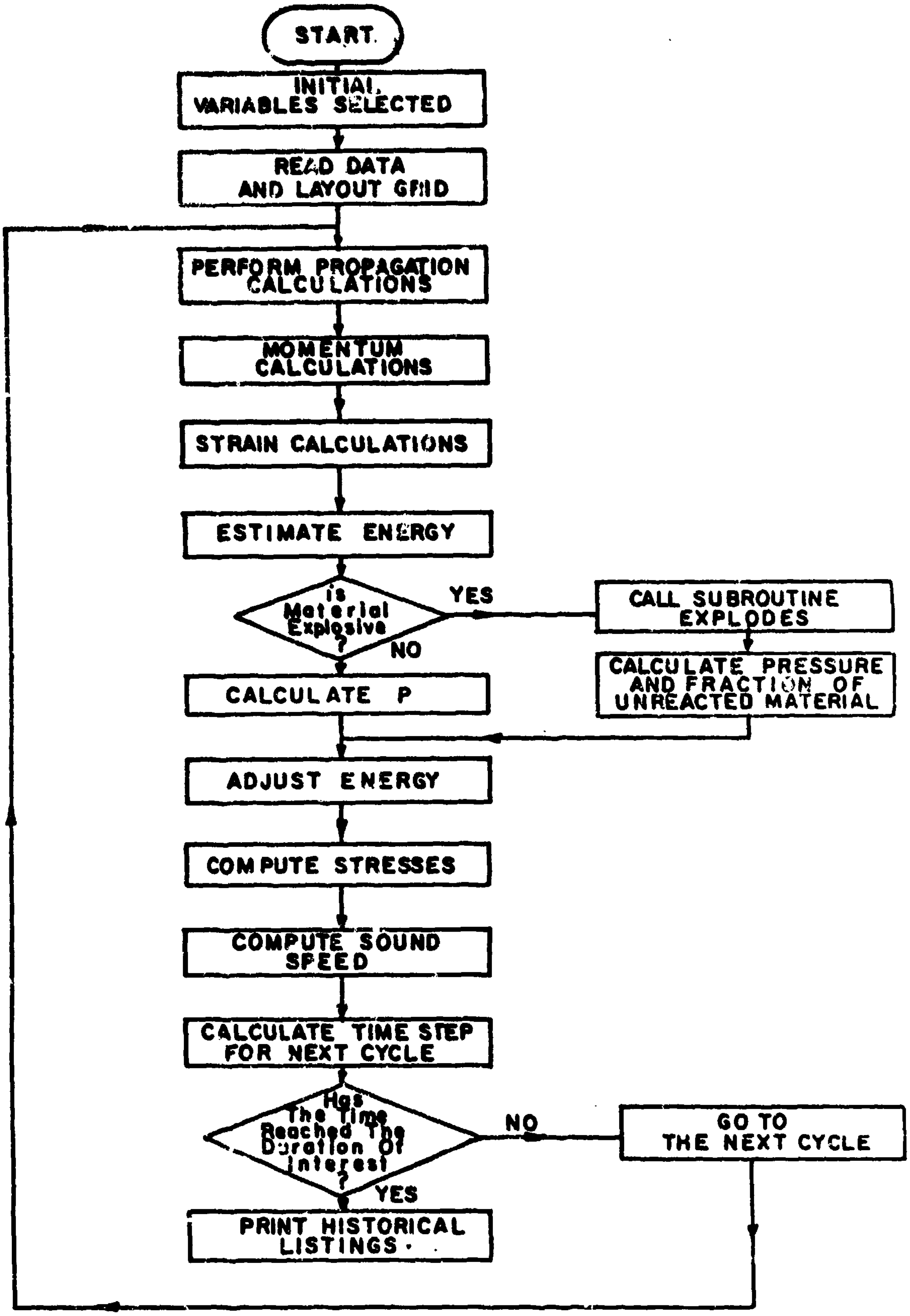
START
INITIAL VARIABLES SELECTED
READ DATA AND LAYOUT GRID
PERFORM PROPAGATION CALCULATIONS
MOMENTUM CALCULATIONS
STRAIN CALCULATIONS
ESTIMATE ENERGY
is Material Explosive ?
YES
NO
CALL SUBROUTINE EXPLODES
CALCULATE PRESSURE AND FRACTION OF UNREACTED MATERIAL
CALCULATE P
ADJUST ENERGY
COMPUTE STRESSES
COMPUTE SOUND SPEED
CALCULATE TIME STEP FOR NEXT CYCLE
Has The Time Reached The Duration Of Interest ?
NO
GO TO THE NEXT CYCLE
YES
PRINT HISTORICAL LISTINGS

FIGURE 12: SIMPLIFIED FLOW CHART OF THE "HYDREL" COMPUTER CODE

compared against the experimental observations. "HYDREL" can produce pressure-time and mass fraction of unreacted explosive time histories for any point of the grid describing the impact. A buildup in pressure and fraction of reacted material in successive points in the explosive indicates events leading to a detonation while decreasing pressures and fraction of reacted explosive indicate a failure.

Table 4 presents the calculated results for some commercial explosives tested. Figures 13 - 16 present the pressure-time and mass fraction of unreacted explosive-time histories for a typical case of a cap sensitive emulsion explosive. The K's represent points along the axis of the charge with the larger K being closer to the interface between impactor and explosive. The larger K = 30 is at the interface. Figures 13, 14 indicate a failure when the projectile travels at 700 m/s while figures 15, 16 indicate a detonation with the projectile travelling at 800 m/s. Runs were also conducted for the case of aluminum projectiles and emulsion A. The critical velocity in this case was increased by a factor of 1.2 which is consistent to quantitative(9) and qualitative experimental observations that aluminum projectiles require higher velocities to initiate an explosive target, compared to higher density metal projectiles.

DISCUSSION AND CONCLUSIONS

From the comparison between experimental and calculated results it follows that the numerical model

EXPLOSIVE	TYPE OF IMPACTOR	DIMENSIONS OF IMPACTOR	VELOCITY OF IMPACT (m/sec)	RESULT
EMULSION A	BRASS PROJECTILE	DIAMETER 13mm	700	FAILURE
		LENGTH 13mm	750	DETONATION
	ALUMINUM PROJECTILE	DIAMETER 13mm	850	FAILURE
		LENGTH 13mm	900	DETONATION
EMULSION B	BRASS PROJECTILE	DIAMETER 13mm	800	FAILURE
		LENGTH 13mm	900	DETONATION
EMULSION C	BRASS PROJECTILE	DIAMETER 13mm	1330	FAILURE
		LENGTH 13mm		
	ALUMINUM FLYER PLATE	THICKNESS:3.2mm	1230	FAILURE
		THICKNESS:3.2mm	1820	DETONATION
		THICKNESS:9.5mm	1660	DETONATION
SLURRY A	ALUMINUM PROJECTILE	DIAMETER 25mm	320	FAILURE
		LENGTH 50mm	440	DETONATION
		DIAMETER 50m	300	FAILURE
		LENGTH 100mm	350	DETONATION
		DIAMETER 100mm	200	FAILURE
		LENGTH 130mm	250	DETONATION
SLURRY B	ALUMINUM PROJECTILE	DIAMETER 25mm	400	FAILURE
		LENGTH 50mm	500	MARGINAL
		DIAMETER 50mm	300	FAILURE
		LENGTH 100mm	350	MARGINAL
			400	DETONATION
		DIAMETER 100mm	250	MARGINAL
		LENGTH 130mm	300	DETONATION

TABLE 4: CALCULATED RESULTS FOR THE HIGH VELOCITY IMPACT OF COMMERCIAL EXPLOSIVES.

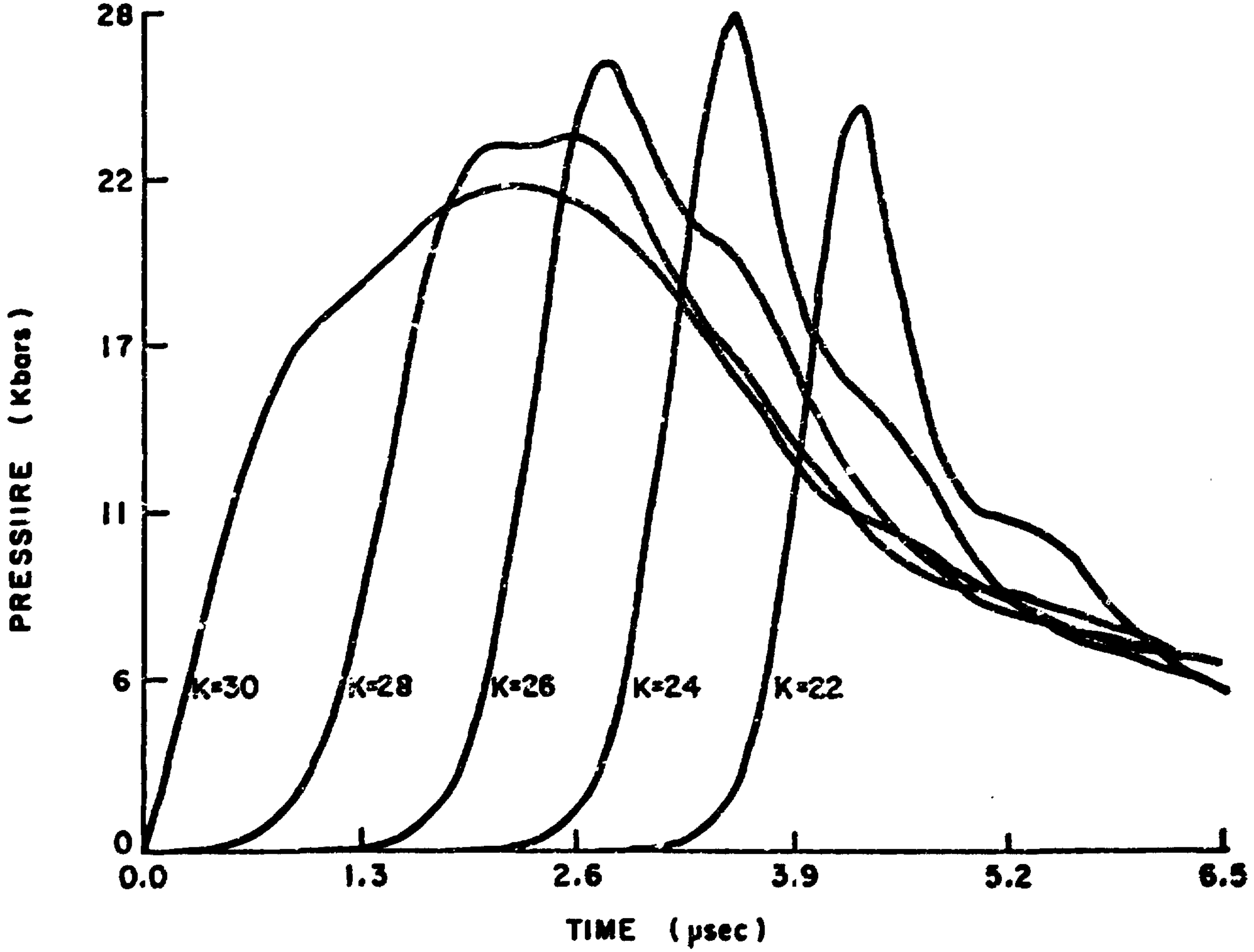

FIGURE 13: PRESSURE TIME HISTORIES FOR EMULSION A. VELOCITY OF PROJECTILE 700 m/sec.

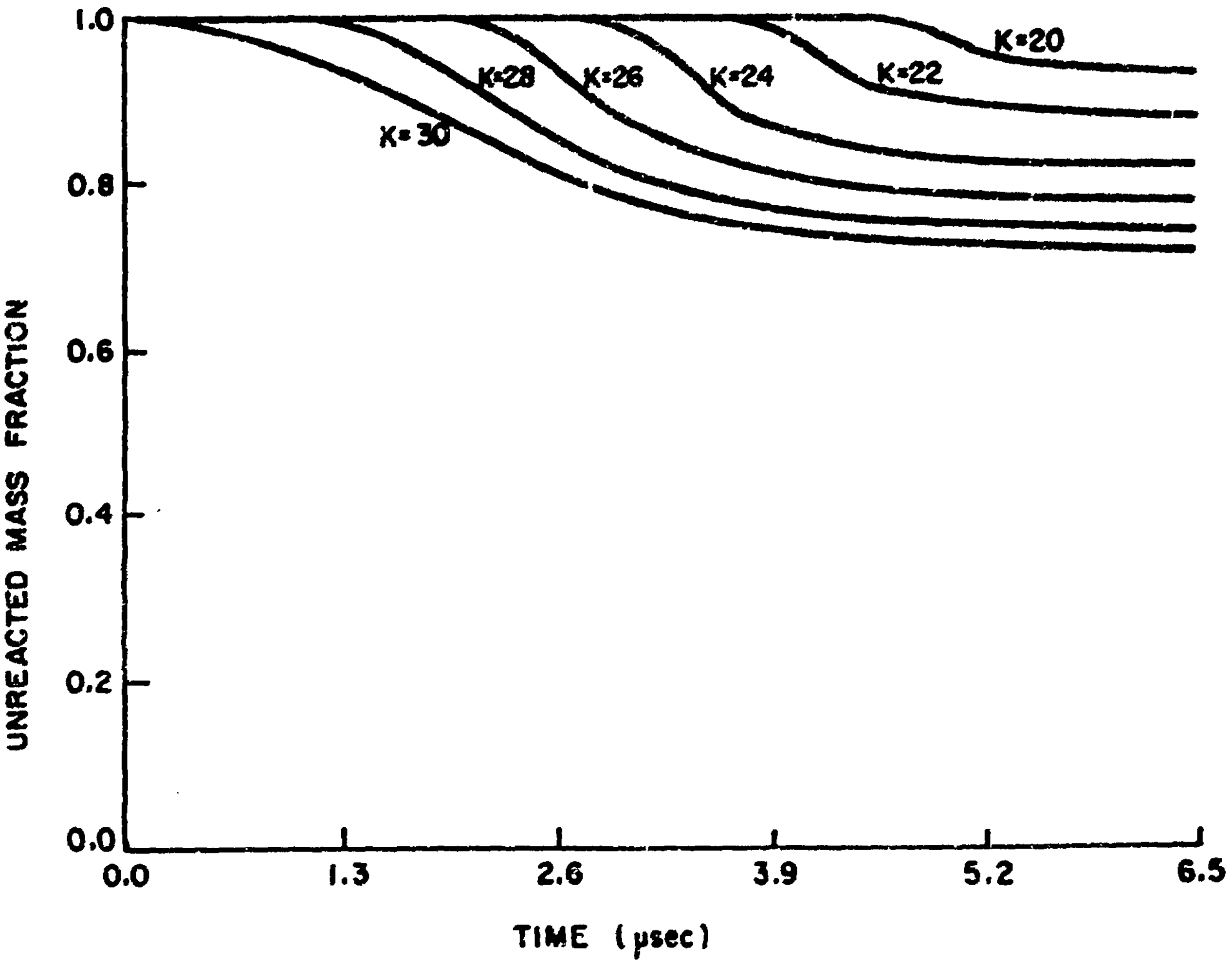

FIGURE 14: MASS FRACTION OF UNREACTED EXPLOSIVE VERSUS TIME FOR EMULSION A. PROJECTILE VELOCITY 700 m/sec.

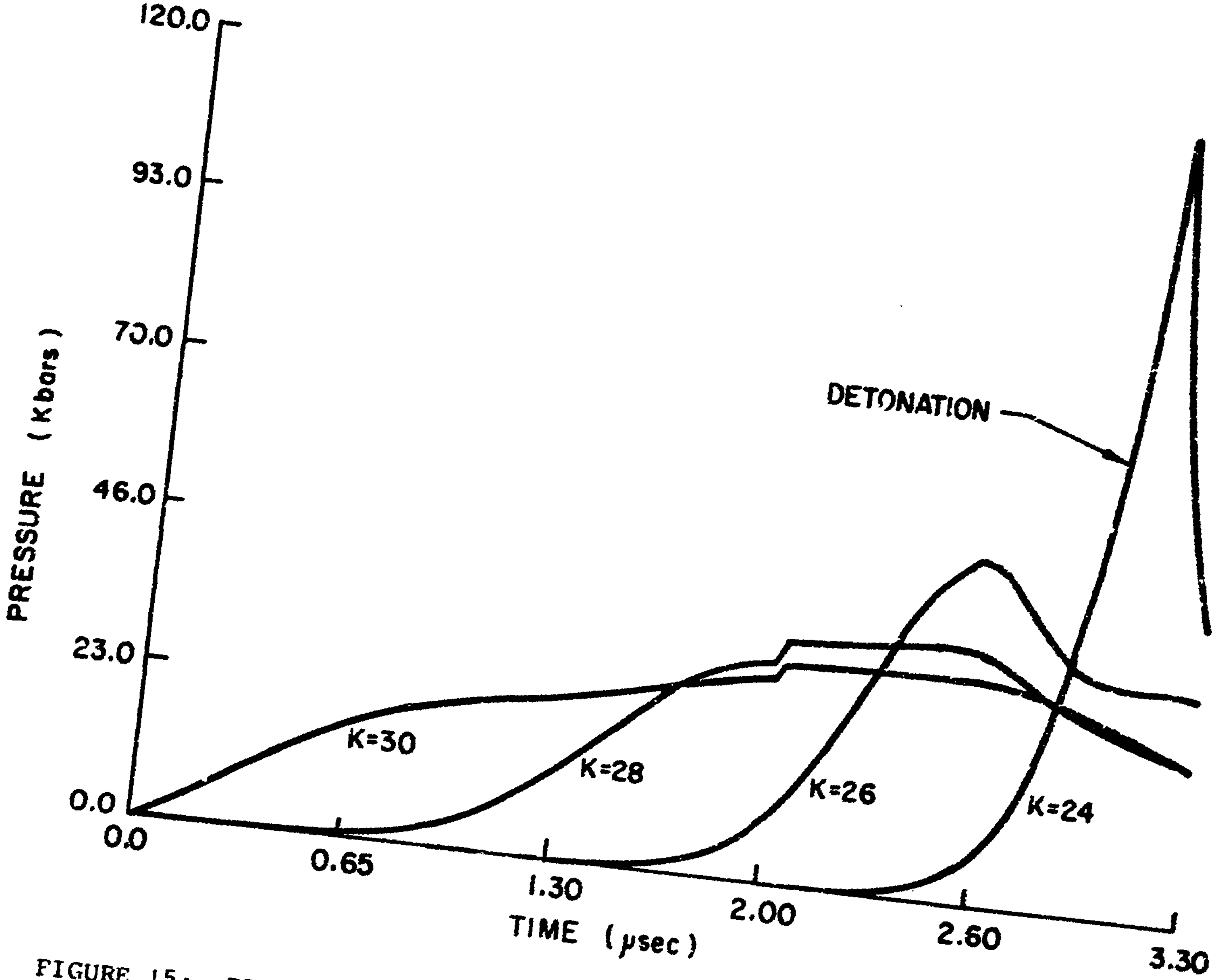

FIGURE 15: PRESSURE VERSUS TIME FOR EMULSION A. PROJECTILE VELOCITY 800 m/sec.

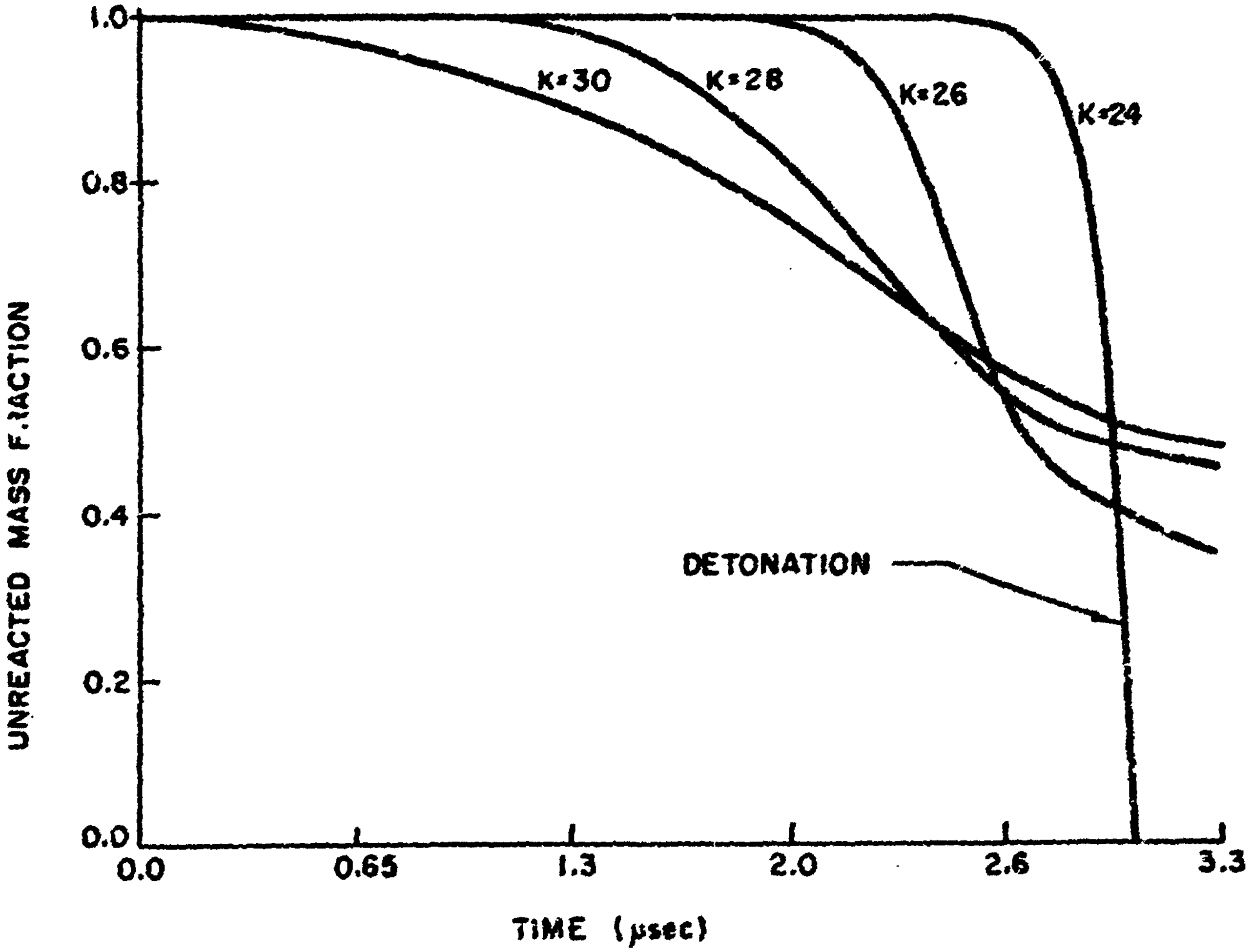

FIGURE 16: UNREACTED EXPLOSIVE VERSUS TIME FOR EMULSION A. PROJECTILE VELOCITY 800 m/sec.

"HYDREL" reproduced the main characteristics of the initiation of the commercial explosives tested. The code predicted the impact initiation with sufficient accuracy. Moreover it demonstrated the dependency of the initiation of the various explosives on the material and geometric properties of the impactor.

It was found that materials of high density (e.g. brass) initiate explosive targets easier than materials of lower density (e.g. aluminum).

The diameter of the projectile was shown to be very important when dealing with small projectiles. This is expected, however, because initiation is influenced by the dimensionality of the experiment. When the diameter is smaller the effect of side rarefactions becomes more obvious. In the calculations, in cases it was observed that when the projectile diameter was small and the impact velocity high, initiation occurred almost immediately on impact. However if the projectile velocity was not high enough, detonation did not propagate but was quenched by the action of following rarefactions.

Flyer plates because of their large area of impact impose a one dimensional impact and initiate the explosives easier. This was demonstrated in the case of Emulsion C. Flyer plate data which were obtained for the cap sensitive emulsion products demonstrated the same effect. These data however were not used in the quantitative comparison because of inaccuracies in the calculation of the plate velocity caused by possible spalling of the metal plate. In the case of a slowly moving explosive driven metal plate, spalling is possible due to insufficient thickness of driver explosive behind the plate.

Blasting cap sensitive emulsion and slurry products are similar with regard to their safety at high velocity impacts. However drop weight tests have shown emulsion explosives to be safer. Therefore the drop weight test should not be used as a single criterion to evaluate impact sensitivity of commercial products.

Another interesting result of the investigation of commercial products is that they were found to be more sensitive than cast military explosives such as cast TNT and cast Composition B. Cast TNT and cast Composition B are not cap sensitive though. It appears that there is a close relationship between cap sensitivity and impact sensitivity.

With regard to the modelling code the most important information is the Pop plot. It was found that Pop plot data could be obtained more easily for emulsion than for slurry explosives. Emulsion explosives consist of a more homogeneous mix containing small liquid droplets sustained in a continuous liquid matrix and microscopic miocroballoons. In slurries the mix is crude containing liquid with large solid objects (prills, pieces of gum etc.) and large voids. These discontinuities can be detrimental in the determination of a

Pop plot. Slurry C which is a slurry containing TNT prills in its mass was a typical example of a product in which the discontinuities produced a very significant scatter of data. As a result it was impossible to obtain a Pop plot for this product. It is rather obvious that Pop plot work is recommended for products which contain small size grains and chemical ingredients uniformly distributed inside the mass of the explosive.

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FRICTION AND IMPACT SENSITIVITIES FOR HIGH EXPLOSIVES

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*Mound is operated by Monsanto Research Corporation for the U. S. Department of Energy under Contract No. DE-AC04-76DP00053.

Understanding sensitivities of energetic materials under specific initiation modes is critical for

- Safe handling and accident prevention during development, production, transportation, and storage.

- Material's design application.

Contd pg. 419

Two major approaches have to be considered in planning for safe handling of energetic materials:

- Establish the necessary conditions to prevent a premature initiation.
- Limit the degree of personnel and property damage that would result if an accident were to occur.

Cont'd

A premature initiation could be caused by one or a combination of the following:

- Impact;
- Friction;
- Electrostatic discharge;
- Heat, etc.

Samples tested:

CP - 2-(5-cyanotetrazolato)pentaammine cobalt (III);

PETN - pentaerythritol tetranitrate;

Barium styphnate;

HMX - cyclotetramethylene tetranitramine;

TATB - 1,3,5-triamino-2,4,6-trinitrobenzene

LX-15 - 95 wt % HNS-I and 5 wt % Kel-F800

LX-16 - 96 wt % PETN and 4% FPC-461

RX26BB - 50 wt % HMX and 50 wt % TATB

RX26BH - RX26BB with a 0.1 wt % each of calcium stearate and graphite; and

PBX of HMX - 96 wt % HMX and 4% FPC-461

Sample parameters:

- Various surface area
- Baking effect
- Aging effect
- Batch difference

The load charges of 50% probability initiation were calculated from the Bruceton one-shot (up-and-down) statistics.

An Example of Bruceton Data for Friction Sensitivity Test (LX-16, ER 7364)

Weight Charge (kg)	Test Number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
8.8		X						X		X										X		X		X
8.0	O		X		X		O		O		X		X		X				O		O		O	
7.2				O		O						O		O		X		O						
6.4																	O							

50% probability: 7.7 kg

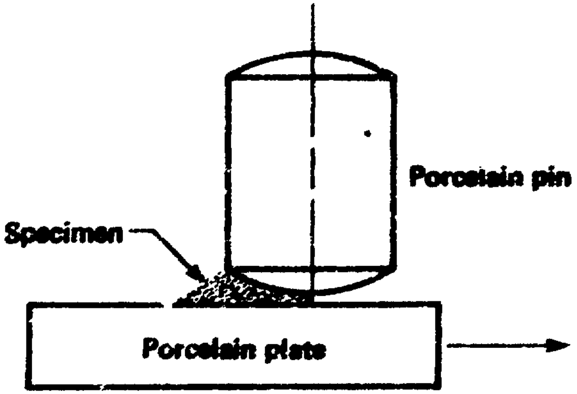
FRICTION SENSITIVITY

A large BAM (Bundesanstalt fur Materialprufung) tester was used for friction tests.

- Six different positions in the tester's arm.
- Weight charge from 0.5 to 36 kg.

Friction test parameters:

- 0.010 g sample used each time.
- Porcelain plate and pin of "standard roughness."
- A path of 10 mm length.



FRICTION SENSITIVITIES OF PETN AND HMX

Explosives	Weight Charge for 50% Probability (kg)	Sample Characteristics
HMX	6.2	6320 cm²/g surface, before baking
HMX	6.1	6320 cm²/g surface, after 100 hr at 100°C
PBX of HMX	6.1	96 wt % of 6320 surface after 100 hr at 100°C and 4 wt % FPC-461
PBX of HMX	7.2	96 wt % of a 930 cm²/g HMX and 4 wt % FPC-461
PETN	8.1	4110 cm²/g surface area
PETN	7.0	31,000 cm²/g surface area
*LX-16	7.7	96 wt % 4110 cm²/g PETN and 4 wt % FPC-461

CONCLUSIONS FOR PETN AND HMX FRICTION SENSITIVITIES

- HMX is slightly more sensitive than PETN.
- Powders of higher surface area are more sensitive to friction than those of the lower surface area.
- Coating with 4 wt % FPC-461 has no effect on friction sensitivity.
- Baking 100 hr at 100°C has no effect on friction sensitivity.

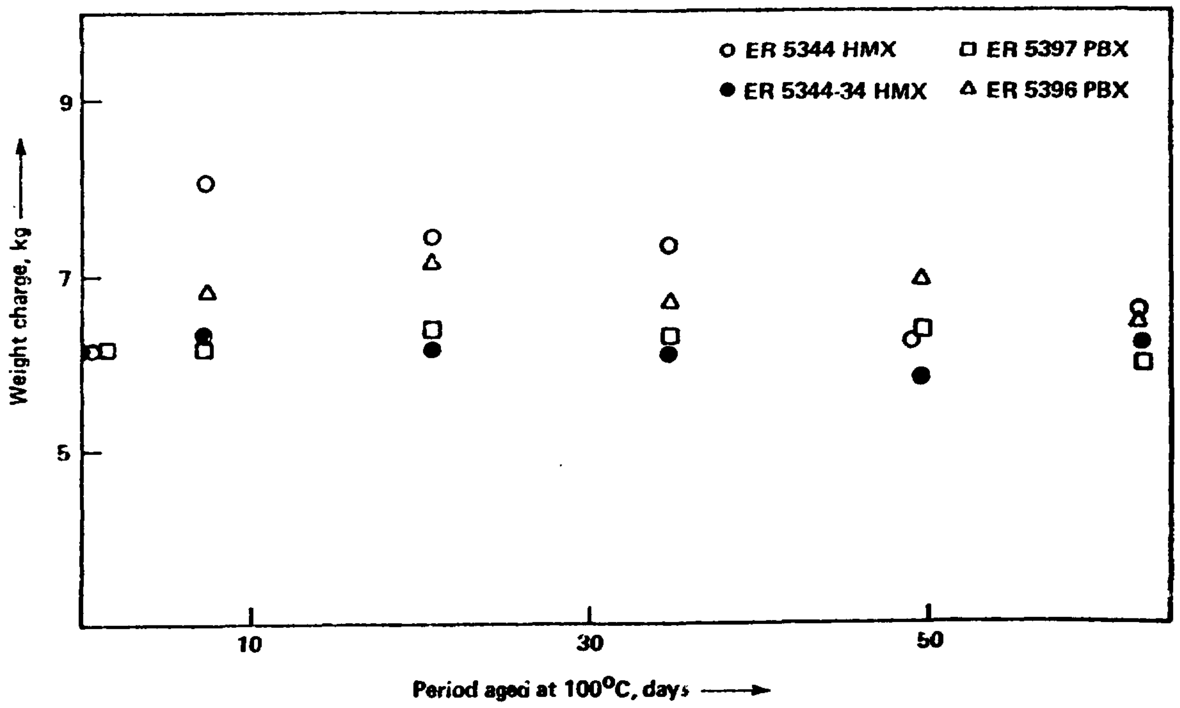
FRICTION SENSITIVITIES OF CP, BARIUM STYPHNATE, TATB, AND LX-15

Explosives	Weight Charge for 50% Probability (kg)	Sample Characteristics
CP	0.9	Unidynamics EL58633
CP	1.3	Unidynamics EL47344
Barium Styphnate	1.7	Chemtronics
Barium Styphnate	2.0	Sandia
LX-15	>36	95 wt % HNS-I and 5 wt % Kel-F800, larger crystal
LX-15	>36	Fine powders
TATB	>36	LLNL-B-592
RX26BB	13	50 wt % TATB and 50 wt % HMX
RX26BH	>36	RX26BB with 0.1% graphite and 0.1% calcium stearate

CONCLUSIONS OF FRICTION SENSITIVITIES FOR CP, BARIUM STYPHNATE, TATB, AND LX-15

- Compared to PETN and HMX, CP and barium styphnate are very friction sensitive, while TATB and LX-15 are insensitive.
- Mixture of TATB and HMX (which is friction sensitive) is more friction sensitive than TATB.
- Blending of this mixture to 0.1% graphite and 0.1% calcium stearate reduces friction sensitivity.
- Batch-to-batch variations.

No effects on impact or friction sensitivities were observed for HMX and its PBX'es after aged at 100°C up to 9 weeks.



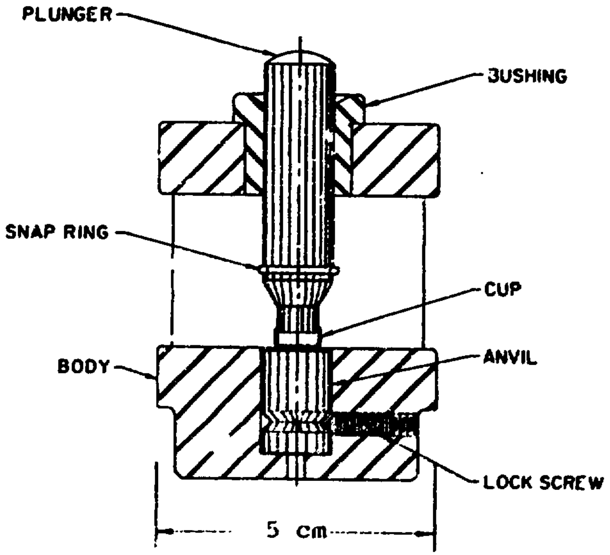
IMPACT SENSITIVITY

A Technoproducts drop-weight tester was used for impact sensitivity tests.

- Drop height: 0 to 50 cm in 0.5 cm increments.
- Weight charge: 1 to 5 kg in 0.1 kg increments.

Impact test parameters:

- 0.020 g sample each test
- Always dropped from 50 cm height
- Results tabulated in cm-kg.



SOLID SAMPLE HOLDER

IMPACT SENSITIVITIES OF PETN AND HMX

Explosives	Weight Charge for 50% Probability (kg - cm)	Sample Characteristics
HMX	160	6320 cm²/g surface, before baking
HMX	176	6320 cm²/g surface, after 100 hrs. at 100°C
PBX of HMX	178	96 wt % 6320 surface after 100 hrs. at 100°C and 4 wt % FPC 461
PBX of HMX	170	96 wt % of a 930 cm²/g HMX and 4 wt % FPC 461
PETN	124	4110 cm²/g surface area
PETN	170	31000 cm²/g surface area
LX-16	120	96 wt % 4110 cm²/g PETN and 4 wt % FPC 461

Conclusion for PETN and HMX Impact Sensitivities

- Powders of higher surface area (lower crystal size) are less impact sensitive than those of lower surface are (longer crystal size).
- Impact sensitivities of PETN and HMX are comparable.
- Baking 100 hrs. at 100°C has no effect in impact sensitivity (?).
- Coating with 4 wt % FPC 461 has no effect in impact sensitivity.

IMPACT SENSITIVITIES OF CP, BARIUM STYPHNATE, TATB, AND LX-15

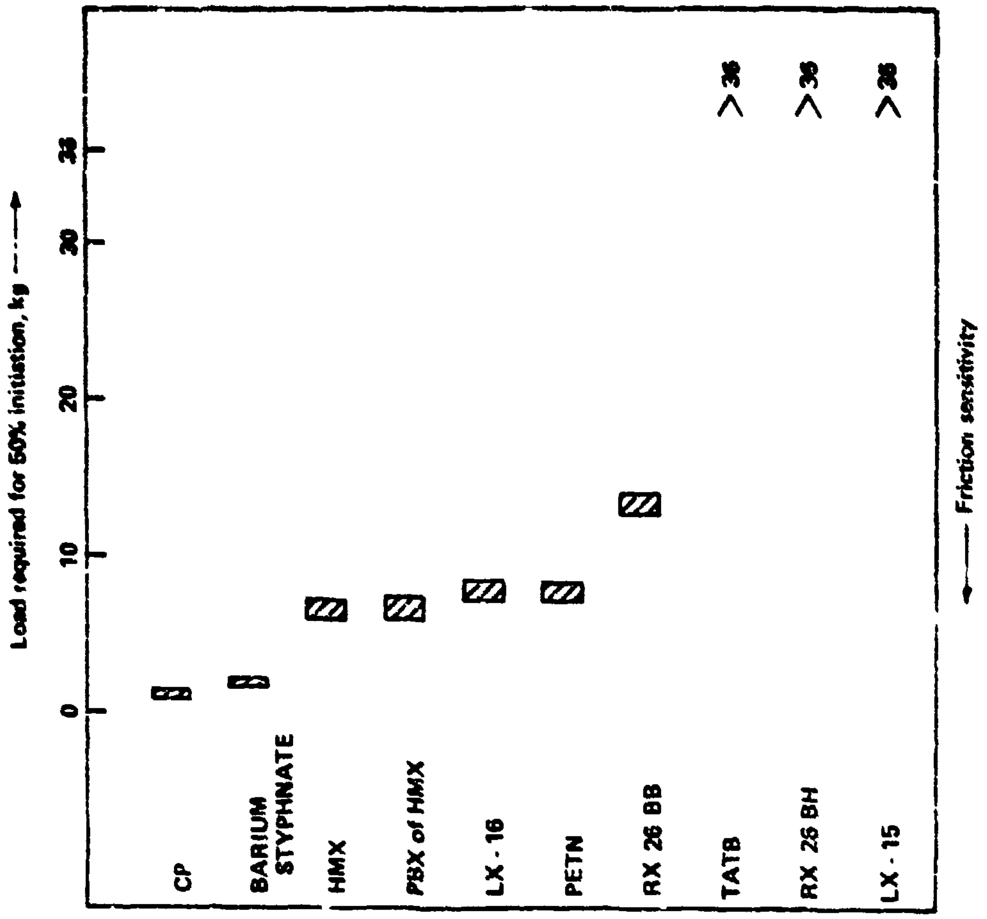
Explosives	Weight Charge for 50% Probability (kg - cm)	Sample Characteristics
CP	66	Unidynamics EI53633
CP	105	Unidynamics EL47344
Barium Styphnate	113	Chemtronics
Barium Styphnate	122	Sandia
LX-15	>250	95 wt % HNS-1, 5 wt % Kel-F 800, larger crystal
LX-15	>250	Fine powders
TATB	>250	LLNL-B-592
RX26BB	>250	50% TATB & 50% HMX
RX26BH	>250	12X26BB with 0.1 % graphite and 0.1% calcium stearate

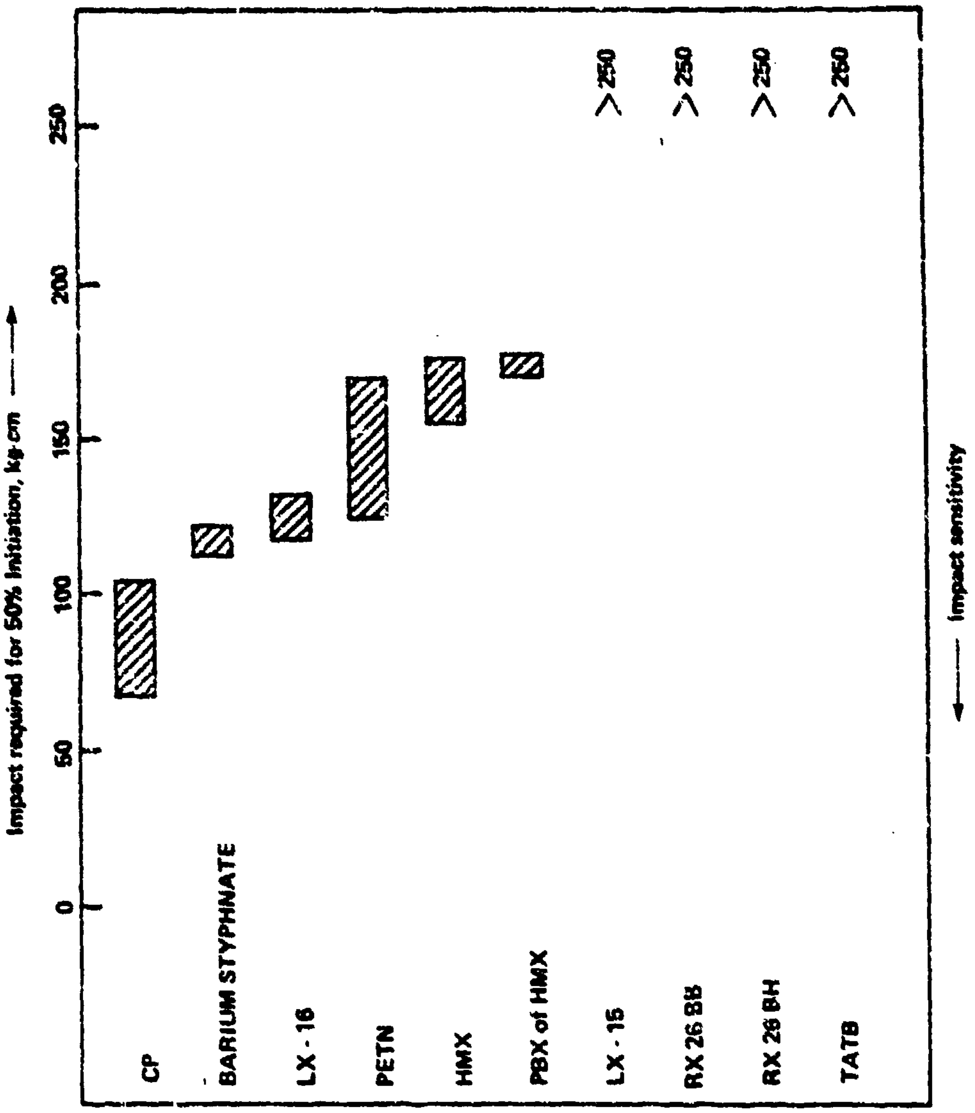
Conclusion for Impact Sensitivities for CP, Barium Styphnate, TATB, and LX-15

- Comparing to PETN and HMX, CP and barium styphnate are very sensitive to impact while TATB and LX-15 are insensitive.
- TATB, LX-15, RX26BB, RX26BH are all out of our test range.
- Batch-to-batch variations.

SUMMARY

- Results for comparative study.
- Both impact and friction sensitivities are surface area dependent.
- No effects by aging (or baking) at 100°C for up to 9 weeks.
- No effects by coating 4 wt % FPC 461.
- Batch-to-batch variations.


Load required for 50% initiation, kg
0
10
20
30
36
CP
BARIUM STYPHNATE
HMX
PBX of HMX
LX - 16
PETN
RX 26 BB
TATB
RX 26 BH
LX - 15
> 36
> 36
> 36
Friction sensitivity


Impact required for 50% Initiation, kg·cm
0
50
100
150
200
250
CP
BARIUM STYPHNATE
LX - 16
PETN
HMX
PBX of HMX
LX - 15
RX 26 BB
RX 26 BH
TATB
> 250
> 250
> 250
> 250
Impact sensitivity

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EQUIPMENT SUPPORT SYSTEMS IN BLAST RESISTANT STRUCTURES

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ABSTRACT

One of the often overlooked elements in the design of a structure to resist the effects of an accidental detonation of high explosives is the mounting and support of the wide range mechanical and electrial equipment installed in the facility. This paper addresses the techniques that should be considered in the mounting of mechanical and electrical equipment and, in particular, will address specific designs which have been utilized in buildings with multiple bays where a detonation in one bay could affect an adjacent bay. In such a facility, the detonation of a high explosive material in one bay could cause injury to personnel and loss of the use of the adjacent bay in spite of the fact that the structure is designed to protect personnel and equipment in those adjacent bays.

INTRODUCTION

When a blast resistant structure is called upon to protect personnel from the effects of a nearby accidental detonation, these effects not only include excessive pressure, thermal effects, and fragmentation but also flying and falling objects from within the protected space due to the externally applied loading. Typical structures in which this situation might occur include control rooms, adjacent production bays, H.E. storage facilities, and similar types of structures.

CONSIDERATIONS

In determining the need for special considerations in equipment mounting, the first step involves the examination of the structure to establish the displacement that is likely to occur during an excursion of the structure caused by an adjacent or nearby detonation. For example, the reinforced concrete dividing wall between two explosive handling bays is in place to protect personnel on either side of the wall from the effects of an explosion on the opposite site. In Figure I(a) the deflection of such a wall is shown. During the design of this wall and based on the maximum credible incident on the opposite face, it can be determined what deflection is anticipated. On a typical wall the deflection may approach 4 inches at the center of the wall. This maximum deflection will occur in 25-30 milliseconds after the structure begins to deflect. The movement of the wall will very closely follow that shown in Figure I(b) where the velocity versus time history for the center of the wall is shown. The wall is initially at rest and is accelerated to some maximum velocity and brought to rest at a point in time corresponding to the time of maximum deflection. The challenge is to determine the maximum acceleration at which an object might dislodge from the wall and become a projectile. Once this maximum dislodging force is determined, a supporting system can be designed to withstand that force such that the object will be either held in place or the supporting system will fail at a level that would prevent the device from becoming a missile within the protected space.

Another consideration is that as the mounting location is moved from the center of the wall to the edge, the displacement and acceleration decreases to a theoretical zero at edges. This is shown in Figure II, where acceleration contours are plotted. Regardless of the type of mounting system proposed, it is beneficial to locate wall attachments as close to the edge as possible. The ultimate solution, of course, is to not mount any devices on a wall that is subject to deflection due to an adjacent bay detonation. Referring to the photograph, the wall at the far end of the room shown is such a wall. Note that there are minimum mechanical and electrical devices mounted on the wall.

In those instances where it is not possible to avoid mounting on a wall subject to deflection, the decision then is whether it is possible to design a mounting system to withstand the acceleration and forces developed in the supportive device or whether it might be better to develop an isolated mounting device to absorb those forces.

ALTERNATIVES

The concept of isolating the installed equipment from the structure can be effective and in many designs a simple method of achieving this can be determined. One approach to isolation would be to construct a frame system within a blast resistant structure which would be totally isolated from the walls and roof which experience deformation. This, of course, would require additional space within the structure resulting in higher construction costs and increased square footage requirements for the facility. Simpler and less costly approaches are to utilize mounting methods and materials compatible with the expected acceleration and forces. The following mounting methods are presented as possible solutions; however, each individual case needs to be evaluated to determine the need for protective mounting and the level of protection desired.

Overhead Supports: Typical devices to be supported overhead include light fixtures and overhead cranes. In considering such installations, it is important to note that the supporting device must be able to support the equipment while it is in normal use and be able to respond to accelerations caused by deflection of the structure following an adjacent bay or exterior detonation. For overhead mounted equipment, the excursion of the structure can be either horizontal as in the case of an adjacent bay detonation or vertical if due to externally applied forces. A simple technique for mounting a lighting fixture, for example, is shown in Figure III. An explosion proof lighting fixture can weigh as much as 100 pounds; consequently, the mounting device, in this case, a bent plate, must be able to remain in its original shape while supporting the light fixture in order that the fixture performs its designed task. However, when subject to an acceleration force, the plate can be designed to experience plastic deformation such that the movement can be withstood and the fixture remains in place. Figure IV depicts a crane rail mount, again affixed to the ceiling of a structure. The sacrificial plate concept as shown can be designed such that the plate experiences plastic deformation at a loading in excess of the dead weight of the crane when fully loaded and in operation.

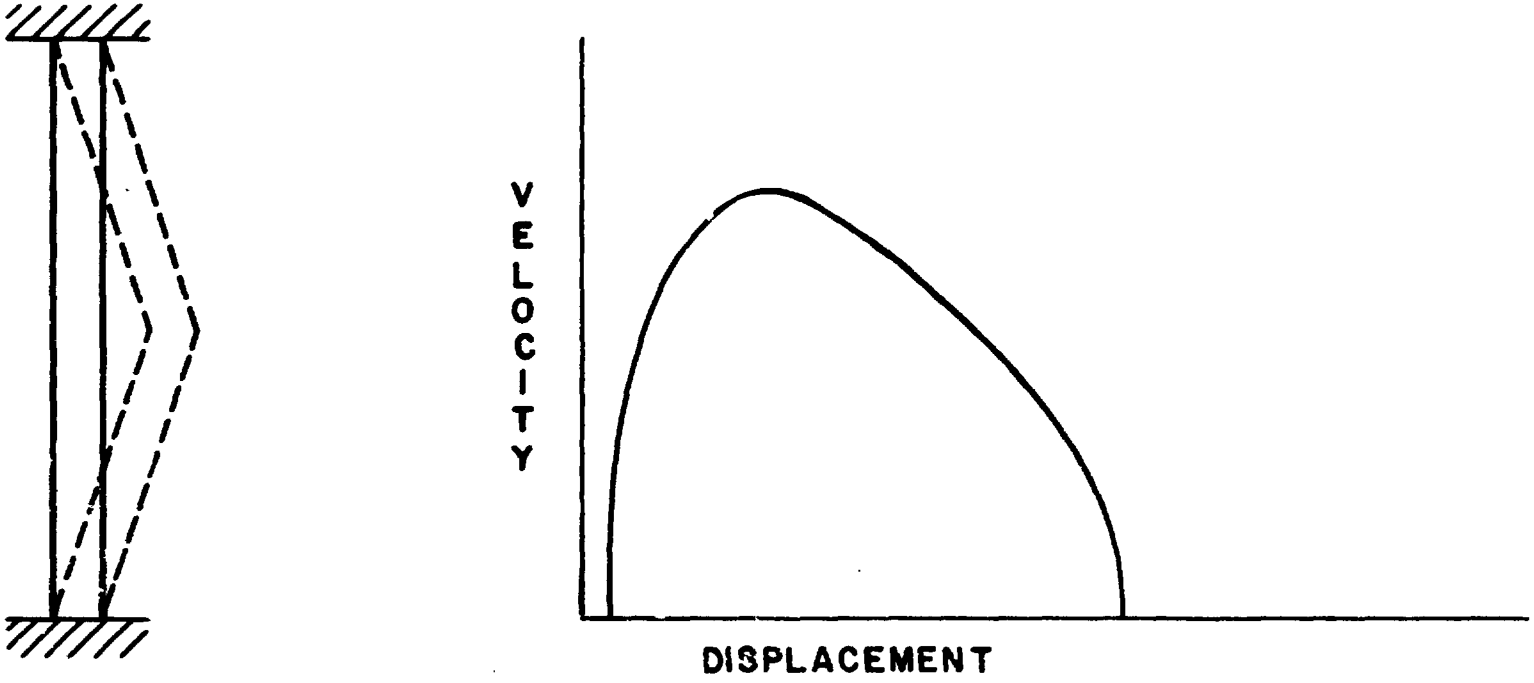
The bolts which extend through the crane supporting beam serve as a safety backup feature in the event the sacrificial plate fails due to fatigue should the structure experience several cycles of excursions due to the adjacent detonation. Figure V indicates alternating mounting methods for other ceiling hung equipment. The top method consists of springs which isolate the load from the structure and can be used where the load on the springs is more or less constant and movement of the device during operation is not a concern. The method shown in the lower half of the Figure utilizes the bent plate concept in which the load is held in a fixed position under normal operation and the plates would only deform in the event of an adjacent bay or exterior detonation causing the ceiling to deform.

Wall Hung Supports: Mounting equipment on walls which are subject to deformation following an adjacent bay detontion require somewhat different considerations. Figure VI shows a typical mounting for duct work, in this case installed on an angle projecting from the wall and held in place by a metal strap. The angle would need to be mounted to the wall with sufficient strength to remain in place during deformation of the wall with the strap installed in such a manner that the duct can move within the strap to a limit equal to the anticipated wall movement. In this way, since the duct is not otherwise connected to the angle, the angle can slide to the right as the wall deflects and the duct would only move due to the friction between the duct and the angle. Note that the space for movement is allowed on both sides of the duct since the wall will initially accelerate and then decelerate as it achieves maximum deflection. This phenomenon goes back to the velocity versus time curve that was originally shown in Figure I. The installation of lighter pieces of equipment such as conduit can be accomplished as shown in Figure VII. In this particular case, the clamp and anchor bolt need to be designed with sufficient strength to hold the conduit in place. An important consideration is the gap as shown between the conduit wall and the concrete. Recalling again the curve shown in Figure I, there is initially a high acceleration rate as the wall begins to deform. This gap permits the wall to move sufficiently that the rate of acceleration has decreased and the conduit hanger then would be able to withstand the forces applied without also deforming to any great extent. The amount of space required and the strength of the supporting strap can be determined utilizing theoretical approaches. In the case of multiple conduits and pipe being mounted on unistrut, a different approach would be required. This is shown in Figure VIII. The weight of the system is such that a direct connection to the deflecting wall would not be desirable. The bent plate method again is applicable in that the bent plate can be designed to support the conduit/pipe system during normal operations but would provide the plastic deformation required to protect those systems in the event the wall begins to deflect.

The photograph shows lighting fixtures and overhead crane rails which have been installed utilizing a bent or sacrificial plate system in a facility where the ceiling of the room is subject to vertical movement due to an adjacent bay detonation.

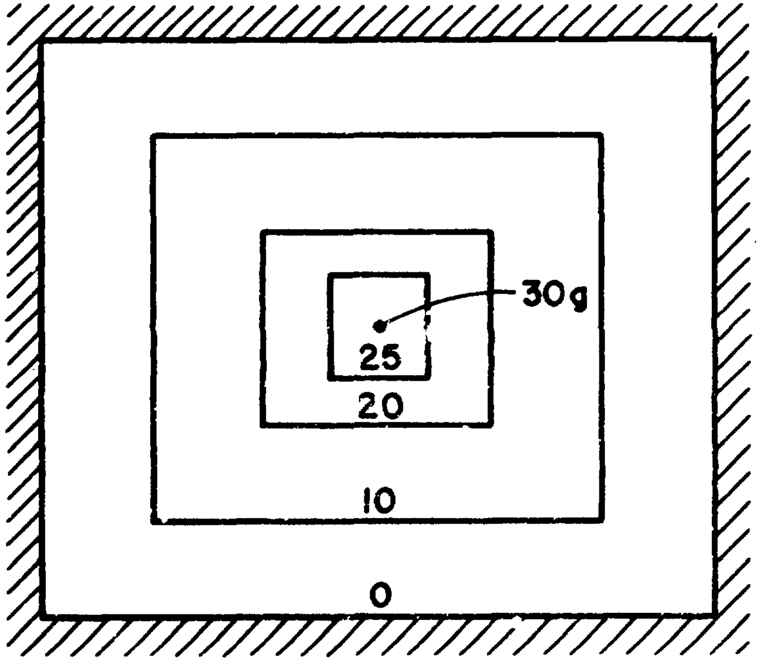
SUMMARY

The purpose of this paper has been to present some ideas relating to installation of mechanical and electrical devices within blast resistant structures. As can be noted from the material presented, there remains to be a number of areas that need to be explored in greater depth before any general solutions can be offered. It is important to recognize the need to install equipment in order that it not become hazardous to occupants of the protected space and each individual case needs to be considered on its own merits. Any comments or suggestions relating to this approach are welcome.



I(a) I(b)

FIGURE 1



WALL ELEVATION
ACCELERATION CONTOURS

FIGURE 11

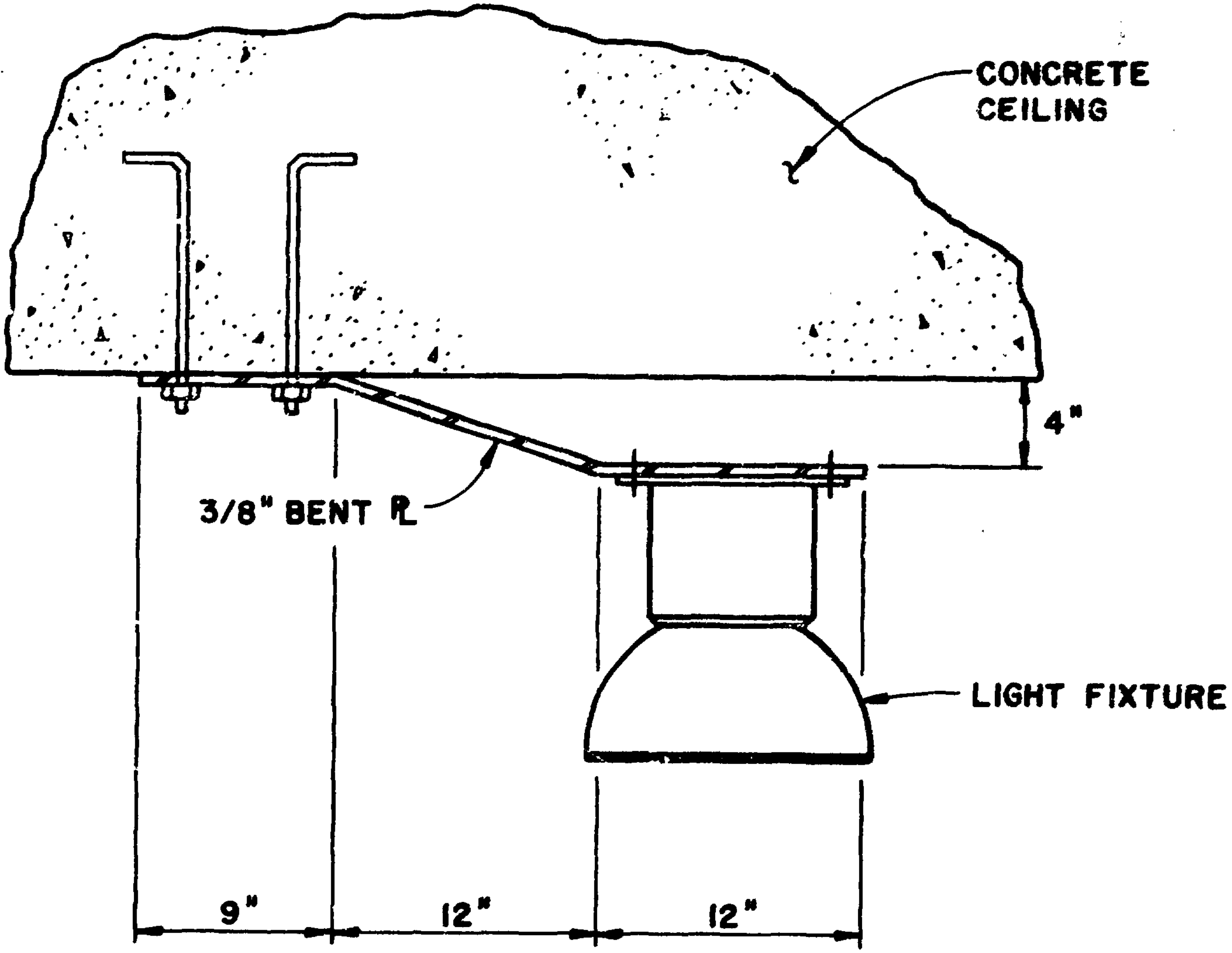


FIGURE III

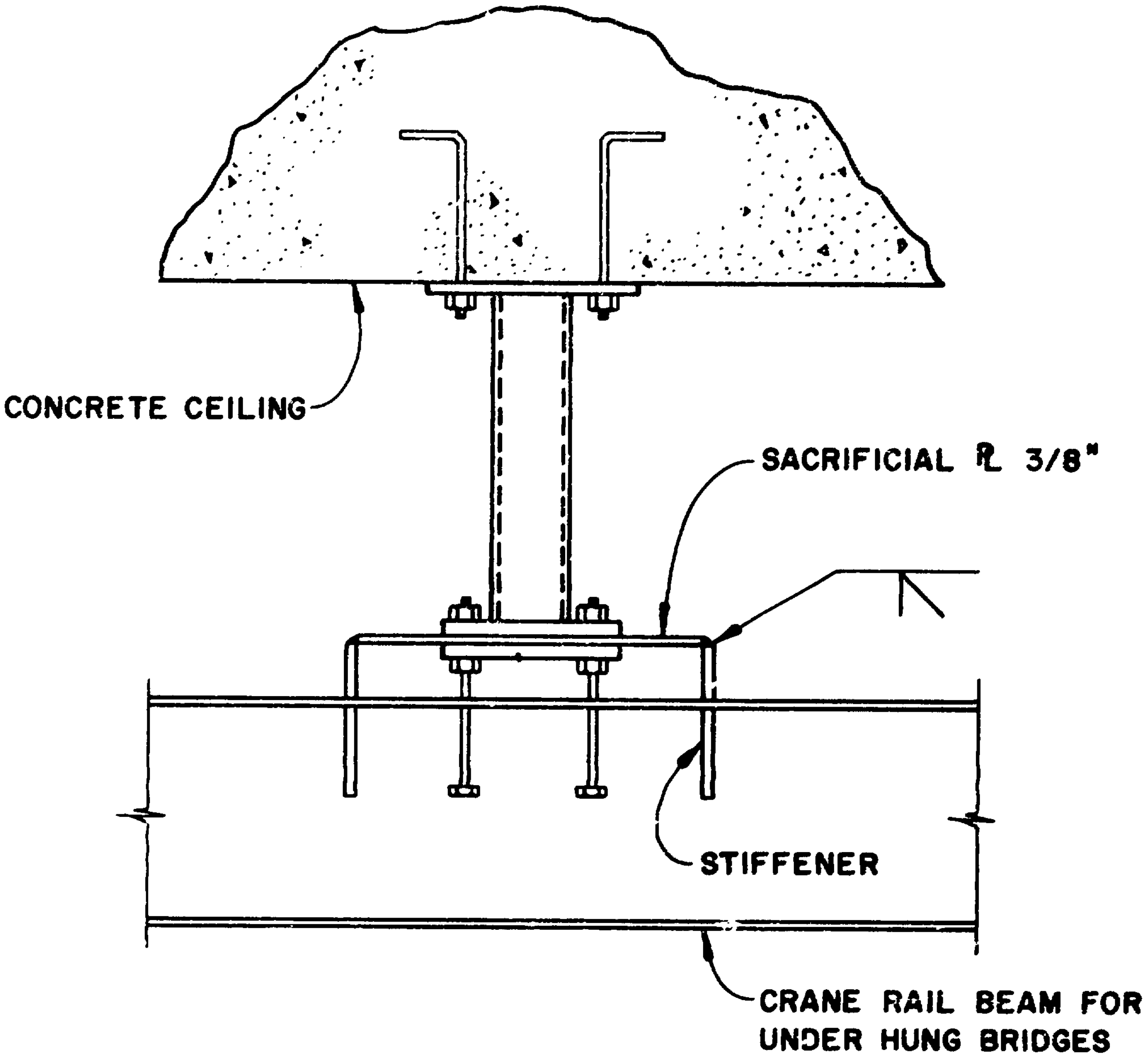

CONCRETE CEILING
SACRIFICIAL PL 3/8"
STIFFENER
CRANE RAIL BEAM FOR
UNDER HUNG BRIDGES

FIGURE IV

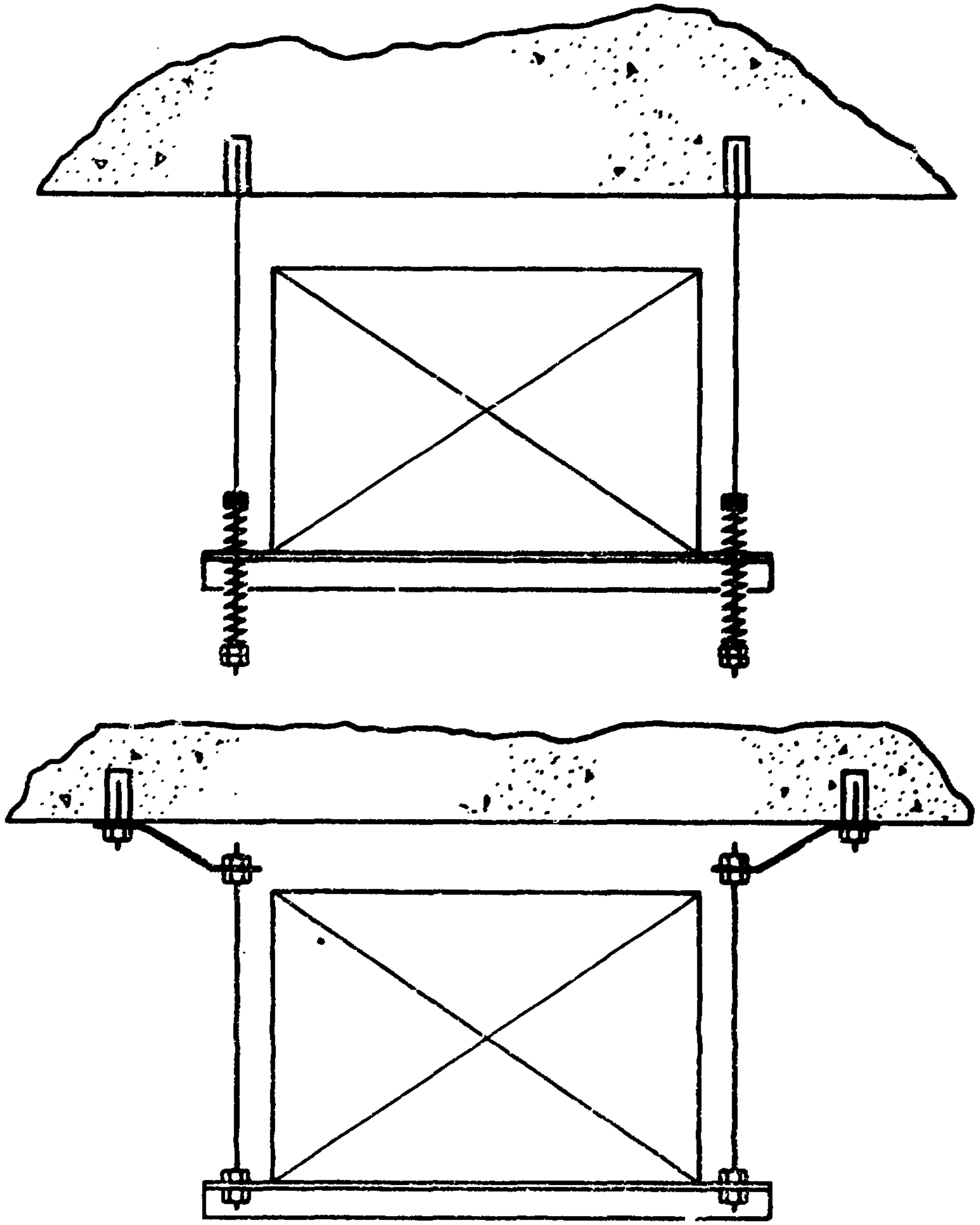


FIGURE V

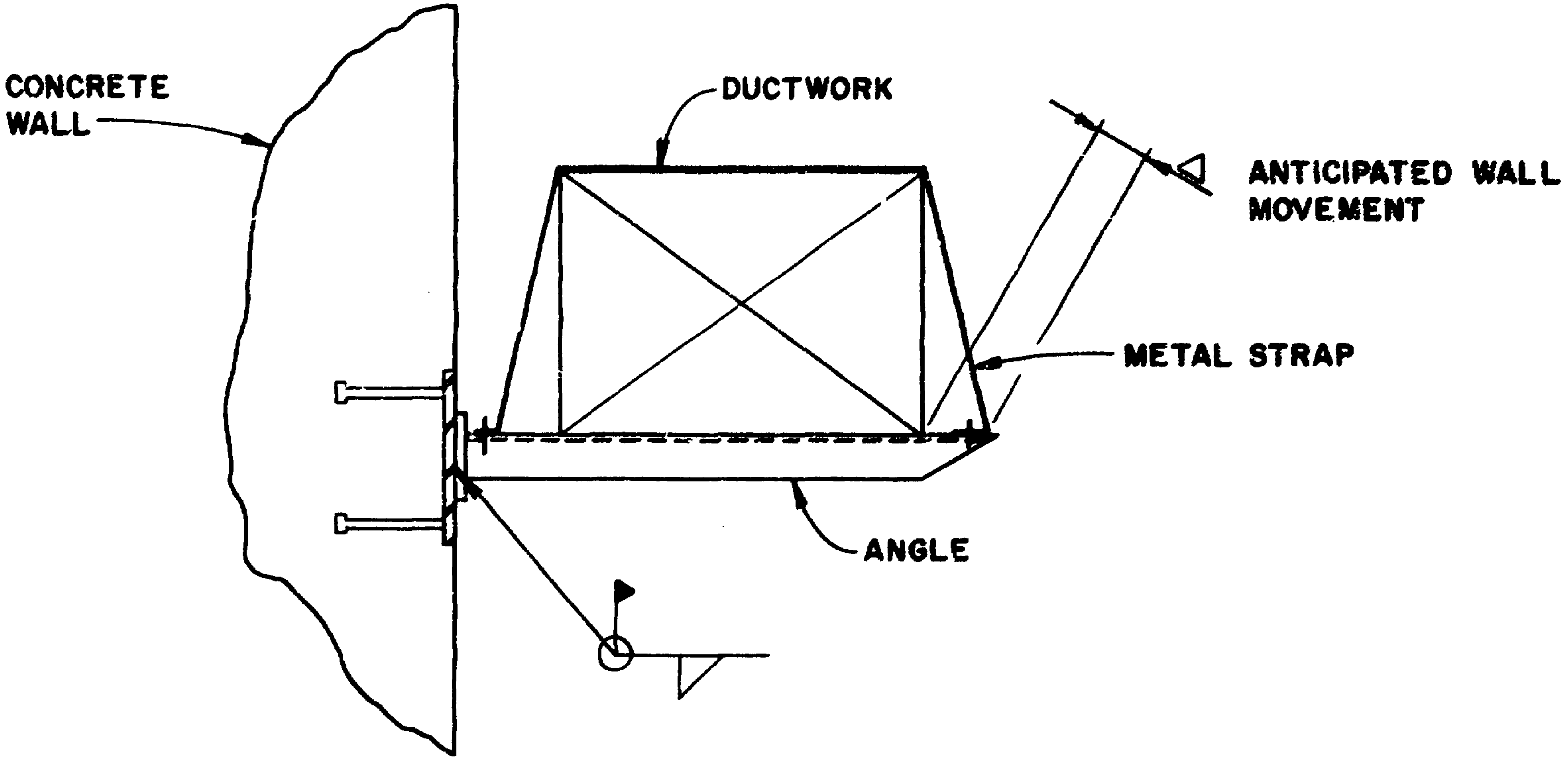

CONCRETE WALL
DUCTWORK
ANTICIPATED WALL MOVEMENT
METAL STRAP
ANGLE

FIGURE VI

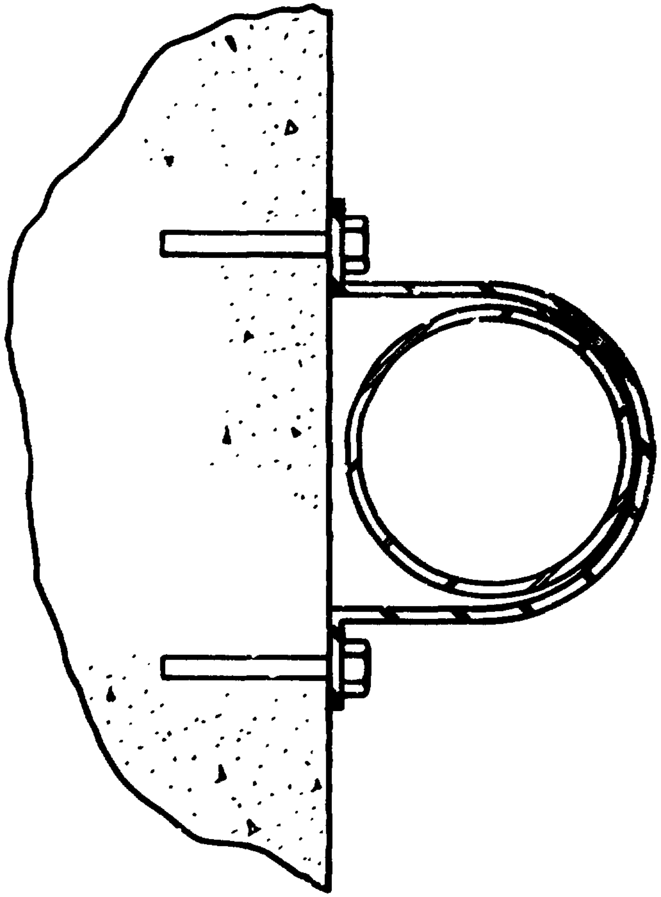


FIGURE VII

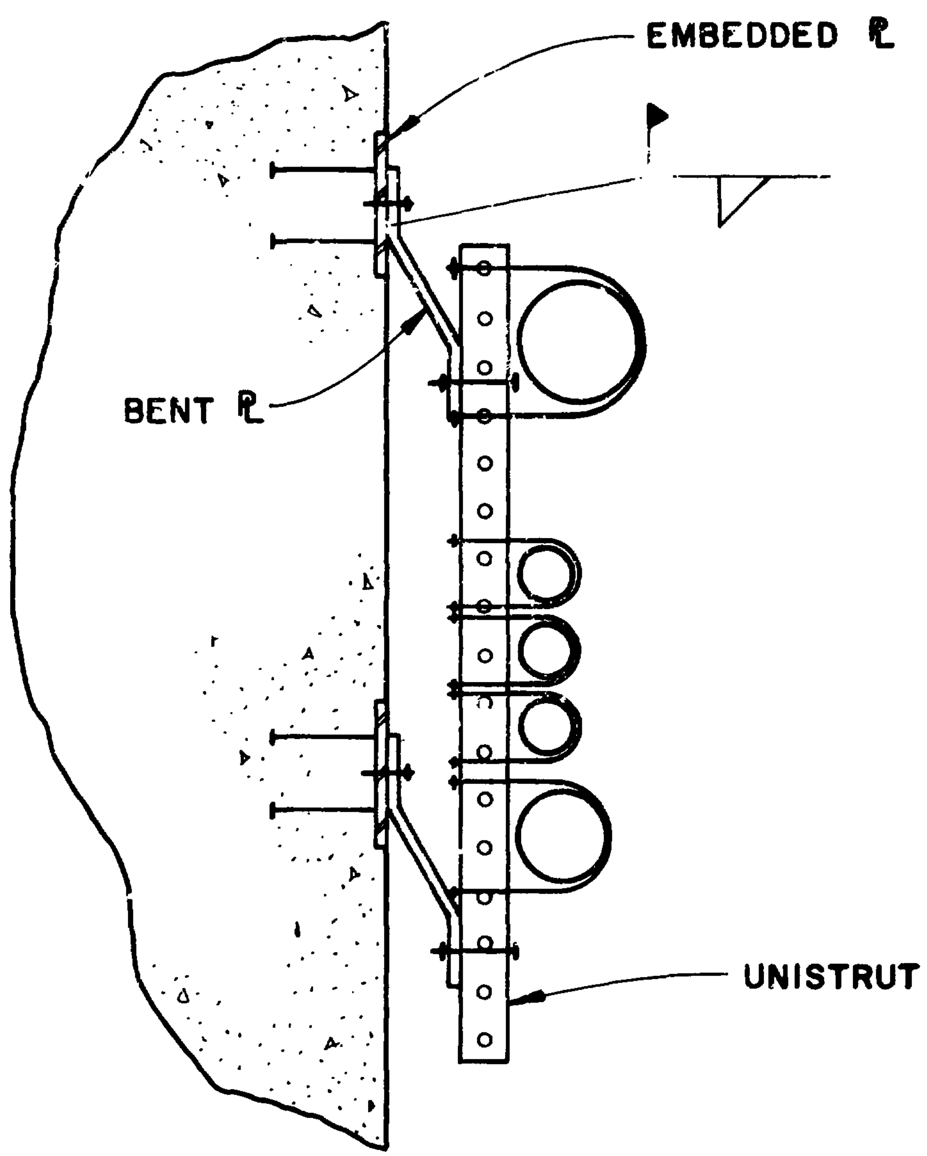
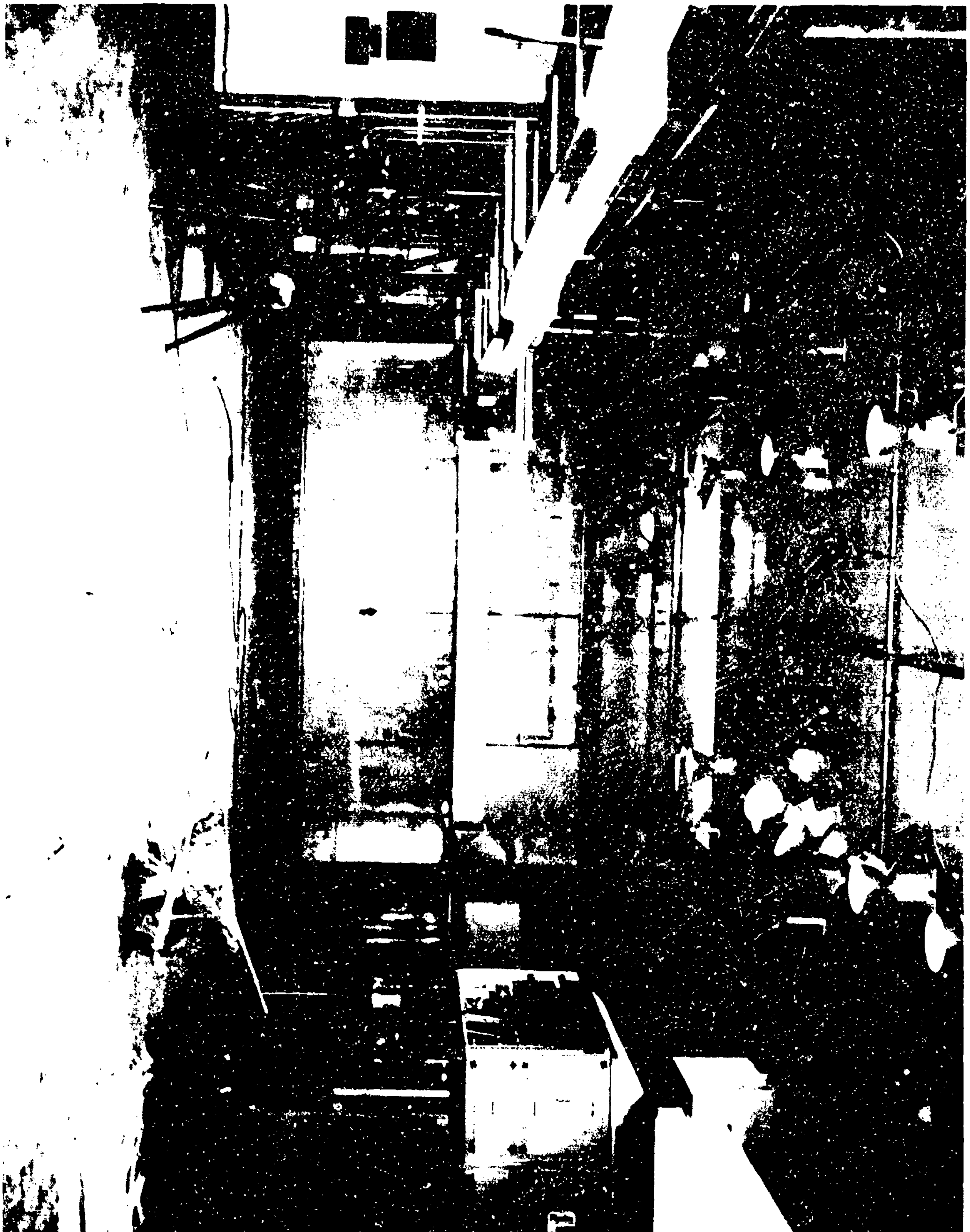


FIGURE VIII



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CONSTRUCTABILITY OF LACED REINFORCED CONCRETE BLAST RESISTANT STRUCTURES

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ABSTRACT

Laced reinforced concrete blast resistant structures have been designed and constructed for many years. Advancement in the state-of-the-art design of these facilities has surpassed advancement in the state-of-the-art in construction of the same, because qualified designers can be selected whereas the selection of contractors is left up to the free market system. To assist contractors through the learning curve of this unique type of construction, certain additional requirements must be built into the contract documents. This paper addresses a number of additional requirements which should be implemented in order to enhance the constructability of laced reinforced concrete structures.

1.0 INTRODUCTION

In today's construction environment, change orders and requests for extra compensation are the rule rather than the exception. It has become imperative that a quality buildable set of contract documents be developed. What makes it even more imperative is the fact that laced reinforced concrete construction is not "normal" construction. Even if you prequalified the general contractors and required that they demonstrate past experience in construction of laced reinforced concrete, there is no guarantee that the ironworkers or the concrete workers have had any experience relative to the demands of this unique type of construction. Therefore, certain construction requirements must be built into the contract documents to avoid impossible situations and enhance the quality.

Impossible situations are those circumstances in which no clear blame can be placed for a specific deficiency and yet further construction progress requires a compromise in the quality of the project. It is analogous to the general contractor driving down the road on a dark night. He has the owner, the resident engineer and the designer in the car with him. All of a sudden they come up to the end of a dead end road. Noboby in the car knows where they made a wrong turn or how they got there. But the fact is that they are on a dead end road. Anyway they turn, they collectively, will lose time and money.

The purpose of this paper is to suggest some ways one may be able to avoid some of these impossible situations in the construction of laced reinforced concrete construction. This paper discusses nine areas where we can enhance the constructability of a project can be enhanced. The first three are basic design considerations and tne last six are construction phase considerations.

2.0 KEEP THE REINFORCING STEEL RATIO NEAR THE MINIMUM

With laced reinforced concrete construction there is enough inherent congestion, simply with the types of bars that must be placed: horizontal and vertical flexural bars, horizontal and vertical diagonal bars, tension bars and lacing (see Figure-1 and Photo-1). When going through the iterative design process, one should think of increasing the thickness of the concrete before increasing the steel ratio. With the present relative cost of steel and concrete, one will always end up with a more economical section if the steel ratio is minimized. In addition to the first cost design benefits, constructability is greatly enhanced, because fewer and smaller bars can be placed and there is more space between the bars to place the concrete.

3.0 USE OUT TO OUT REBAR RIB DIMENSIONS

The intersections of walls, floor, and roof are very busy. Every set of bars that passes through or terminates at an intersection has to have its own plane or layer. The summation of the layers at any intersection cannot exceed the repetitive spacing. This seems to be fundamental, but many intersections which are marginally acceptable using nominal bar diameters are not acceptable for construction. Murphy's Law comes into play here and somehow the ribs of all of the bars manage to line up, and the intersection becomes physically impossible. The layering of the reinforcing steel at intersections must be checked during the design phase using the out to out diameters of the bars. It is also advisable to allow an extra inch of free space to account for irregularities in the fabrication of the bars.

4.0 STANDARDIZE BAR SPACING THROUGHOUT THE STRUCTURE

Standardizing the bar spacing is a feature that isn't adequately appreciated by most designers. In conventional construction, structural engineers are conditioned to optimize the spacing of the bars, such that the steel can be minimized. In so doing, a variety of spacings results, none of which have a common denominator. However, field conditions are such that minor adjustments can be made to avoid interferences. Unfortunately, in laced concrete construction, we don't have that luxury.

It is more important to make the structures constructable than it is to shave a few pounds of steel. Since wall bars have to mesh with roof bars, floor bars and other wall bars, it is very important to have compatible spacings. It is strongly recommended that the designer establish a standard spacing for the entire structure such that bar systems will mesh. It is also recommended that as large a bar spacing as permissible be used, in order to facilitate placement of the concrete. Twelve inches is suggested as a minimum spacing.

5.0 REVIEW OF SHOP DRAWINGS

Design plans contain most of the important design and construction requirements, but designers still cite standards like ACI or ASTM for standard practice and routine details. The shop drawings are the designer's last chance at reviewing the materials which are to be supplied. Of particular concern are the reinforcing steel shop drawings.

These documents need to be reviewed with an eye for constructability. Naturally, the contractor is interested in providing as few pounds of steel as possible if he is operating under a lump sum contract. There is a tendency to eliminate lap splices if possible, but in some cases, it may hinder constructability. No one is more familiar with the design than the designer himself and he must visualize assembling the rebar cage and suggest locations where splices would be advisable and permissible.

6.0 REINFORCING BAR TEMPLATES

As a part of the contract documents, it is advisable that a requirement for reinforcing bar templates be provided for field inspection. The fabricator should be required to spray paint the end of a bar in the bundle of bars which he certifies as most closely corresponding to the geometry defined on his shop drawing. The General Contractor should also be required to field compare the remaining bars in the bundle to the template in the presence of a government inspector. Bars which do not correspond, within defined limits, to the template bar shall be returned to the fabricator.

This procedure accomplishes two things:

1) It alerts the fabricator to the fact that quality control is being taken seriously on this project, and he may make a little more effort in producing a quality product.

2) It also assures that the bars, to be placed, are within the required tolerances before they are assembled.

Beginning the rebar cage assembly with bars that you know are going to work is very important. The assembly of laced reinforcing cages is a very labor intensive job. In the case of the lacing bars themselves, it is extremely difficult to detect which ones are out of alignment until the contractor is ready to place the forms. At this time, it becomes very apparent which bars protrude excessively from the cage. If the contractor is directed to correct the problem, he may have to completely disassemble the cage to remove the defective bars. In some instances, this may not be possible as the lower lacing bars have already been cast in the concrete floor slab.

The requirement of using rebar templates cannot be left up to the good judgment of the contractor and must be included in the specifications.

7.0 CONCRETE WORKING PADS

The most applicable design document, TM 5-1300, suggests the use of optional working pads under the rebar cages. It is further suggested that working pads be made a contract requirement for a couple of reasons:

1) The rebar cages are usually quite heavy and may take several weeks to fully assemble. With this length of time, there is ample opportunity for Mother Nature to disrupt the support of the cage.

2) A working slab under the entire floor slab is even more desirable if a capillary water barrier and vapor barrier are to be provided. During the assembly time, the vapor barrier can be punctured or torn. Once torn, adequate repair is difficult due to the presence of the reinforcing steel. The working slab can also serve as anchorage for sway cables for the wall bars (see Photo No. 2).

The added expense of the 3 to 4 inch working pad is not as great as it would appear. With the presence of a continuous working slab, the required concrete cover for the floor slab can be decreased, essentially trading part of the floor concrete for the working pad. The working slab doesn't need to receive any labor intensive finish. A screed finish is all that is necessary.

The added expense of the working slab is money well spent on quality control. One can refute this statement by saying it is the contractor's responsibility to deal with acts of God, but acts of God seldom help you get a project back on schedule.

8.0 REBAR CAGE ASSEMBLY

For the most part, the designer can't be so specific that he tells the contractor how he is to assemble the cage, but some helpful hints at the preconstruction conference can prove beneficial. For example, many contractors are accustomed to assembling bar cages horizontally on the ground wiring up every joint and then lifting the cage vertically. Due to the nature of these cages, it is best if the cage is assembled in place. It is also not advisable to wire up every intersection until the entire cage has been assembled. Frequently, bars have to be shifted back and forth to accommodate the insertion of other bars. This is especially true at junctures between two walls or a roof and a wall.

Recognizing the fact that these bars have to be shifted back and forth, it is especially desirable to proceed with construction in a manner which will allow this flexibility. Visualize a wall placement which needs to be accomplished in two concrete lifts as in the case of Photo No. 3. If the second concrete lift is placed prior to assembling the roof steel, there will be no flexibility in the wall bars which are anchored into the roof. Therefore, they are fixed in whatever spacing they were in when the concrete was cast. Quite often, a so-called 12 inch spacing will vary plus or minus an inch. The intersection between a roof and a wall is so congested that this inflexibility will bring about some impossible situations. (Photo No. 4 shows a situation where the roof bars were placed, after the second lift on the wall was cast. The number of people required to place these bars is a slight indication of the degree of difficulty.) These same vertical wall bars are usually large bars, if not bundles of large bars. These large bars are not meticulously fabricated and 90 degree bends are not perfect 90 degree bends and are not parallel with the 90 degree bend at the other end of the bar. If the wall concrete is cast to the top, there isn't any flexibility to persuade the bent bar into a compatible orientation with the horizontal roof bar.

Depending upon the complexity of the rebar design, it may be advisable to contractually obligate the contractor to set his formwork and place the roof steel prior to casting the last wall lift.

9.0 BACKUP EQUIPMENT

Placing of the concrete is another critical step in the construction process. The location of construction joints is an important consideration in the design process and the construction needs to be continuous between these predetermined locations. To assure this kind of continuity, certain provisions need to be made in the contract documents:

1) If the concrete placement equipment can break down, backup equipment needs to be on hand. For example, if a concrete pumper is used a backup pumper should be on site for the day of the placement. This is not as expensive as it may seem. As backup equipment, only one equipment crew needs to be present, which makes the rental rate lower. If a crane is already on site and the job can be accomplished with a bucket and tremie chute, the backup equipment for the pumper could be the addition of a bucket.

2) The contractor should be required to supply in writing his plan for providing the concrete material to the site prior to the concrete placement. This may seem rather fundamental, but in the heat of the construction effort, it may not get adequate thought and one doesn't want any miscommunication between the contractor and the material supplier to occur. If

you know in advance that there is going to be a batch plant on the site, it may not be as serious of a requirement.

3) Other additional backup equipment needs to be on hand like additional vibrators, or a backup power source for the vibrators. It has been known to happen that a vibrator has become hopelessly tangled in the rebar, cut off and abandoned in place.

10.0 CONCRETE PLACEMENT TECHNIQUES

Properly placing the concrete within the forms and between the bars is a difficult task. Normal concrete wall construction with temperature steel on both faces will run approximately 75 pounds of steel per cubic yard of concrete. In laced reinforced concrete construction, the ratio may be as high as 450 pounds of steel per cubic yard of concrete. Tension bars down the middle, diagonal bars at the corners, lacing bars and 45 degree cants at the corners are all unique to this type of construction and contribute to the complexity. Proper delivery of the material and adequate vibration are the most challenging tasks.

The delivery system most frequently chosen by a contractor is pumping. This is a good choice because the space between the bars is minimal and the smaller 4 inch diameter hose can physically fit. The material is under pressure and will flow at a desirable rate. If a bucket and a 4 inch tremie hose was used, the concrete might set before it flowed by gravity through the hose. One problem with the pumping system is that the flexible rubber hose isn't always cooperative and wants to go sideways as it is snaked down between the upper wall bars. When placing the first lift in a wall placement, the delivery system, or hose, really needs to get past the floor diagonal bars such that the 45 degree cants become completely filled.

A recommendation for this dilemma is to preset 4" diameter pipes at 4 to 6 foot spacings within the rebar cage down to the desired level and prior to erection of the last wall form (see Figure No. 2). These pipes can be used to convey the material to the bottom of the forms and be retracted as the placement progresses. A not quite as effective alternate to this approach is to attach a rigid section of pipe, say 10 feet long, to the end of the pumper hose. This will greatly assist in inserting the hose in between the rebar.

Once the concrete has been placed at the desired levels, it needs to be adequately vibrated. It has been observed that no less than 4 vibrators and operators are necessary to keep up with one pumper placement in a wall. The concrete should not be placed in lifts greater than 2 feet and each lift has to be vibrated. The lowest lifts are the most difficult to vibrate and are the lifts that need it the most because of the congestion and the 45 degree cants. The problem primarily arises from the fact that the vibrator cannot be moved laterally along the length of the wall because of the shear reinforcing, whether it be lacing or stirrups. The vibrator needs to be lifted vertically the full height of the placement and lowered in between each set of vertical bars. After a while, this becomes very fatiguing for the laborer and unless he has a backup, he will start looking for corners to cut, and not do as effective a job as he should. Without adequate vibration, honeycombing most certainly will occur.

Another problem associated with placement of the concrete is control of the depth of each concrete lift. As concrete is being placed in the forms, the inspector hasd a difficult time gaging the depth of each lift. Unless you have predetermined marks on the rebar cage, the field inspector doesn't have any active leverage with the job foreman. One suggestion is to have a prepainted #3 bar placed horizontally in the rebar cage to designate each permissible lift.

11.0 SUMMARY

The construction of laced reinforced concrete structures differs sufficiently from conventional construction in that additional considerations need to be added to the contract documents and further quality control measures taken during construction to assure a quality, finished product. Among these considerations are the following:

1) The designer needs to proportion his sections to minimize the steel ratio.

2) Intersections need to be checked for interferences using out-to-out bar diameters.

3) The designer needs to standardize the bar spacings throughout the structure.

4) The reinforcing steel shop drawings need to be reviewed with insight towards the ability to assemble the complete rebar cage.

5) The contract documents should require that the fabricator designate one bar in each set as a template to which the remaining bars are to be compared. This field check of the fabrication of the bars should be performed in the presence of a field inspector. Bars out of tolerance shall be returned to the fabricator and proper bars used.

6) Serious consideration should be given to requiring the contractor to provide concrete working pads underneath the walls and floor slabs. It should not be left up to the judgment of the contractor.

7) Serious consideration should be given to presenting an orientation session to the contractor at the preconstruction conference on the problems and advantages of certain rebar cage assembly techniques. For structures with heavily reinforced walls and roofs, consideration should be given to making it a contract requirement to assemble all of the roof steel prior to placing the last concrete wall lift.

8) Since it is very important to maintain continuity between designed construction joint locations, backup equipment such as spare concrete pumper, spare vibrators and auxiliary power, must be on hand during the concrete placement. The only way to assure this is to place the requirement in the contract documents.

9) Placement of the concrete is a critical step in the construction process and it has one of the greatest time constraints. Delivery of the concrete to the proper level within the forms and the subsequent adequate vibration can be very difficult tasks. A minimum number of vibrators (4) and operators should be specified. The designer should consider other means of assuring that the concrete can be transported to the appropriate level within the forms and describe those means in the specifications.

Construction of laced reinforced concrete structures is a very difficult task for even the most knowledgeable contractor. It is believed that incorporation of the above suggestions will certainly enhance the quality of the finished product, and stem some of the construction change orders.

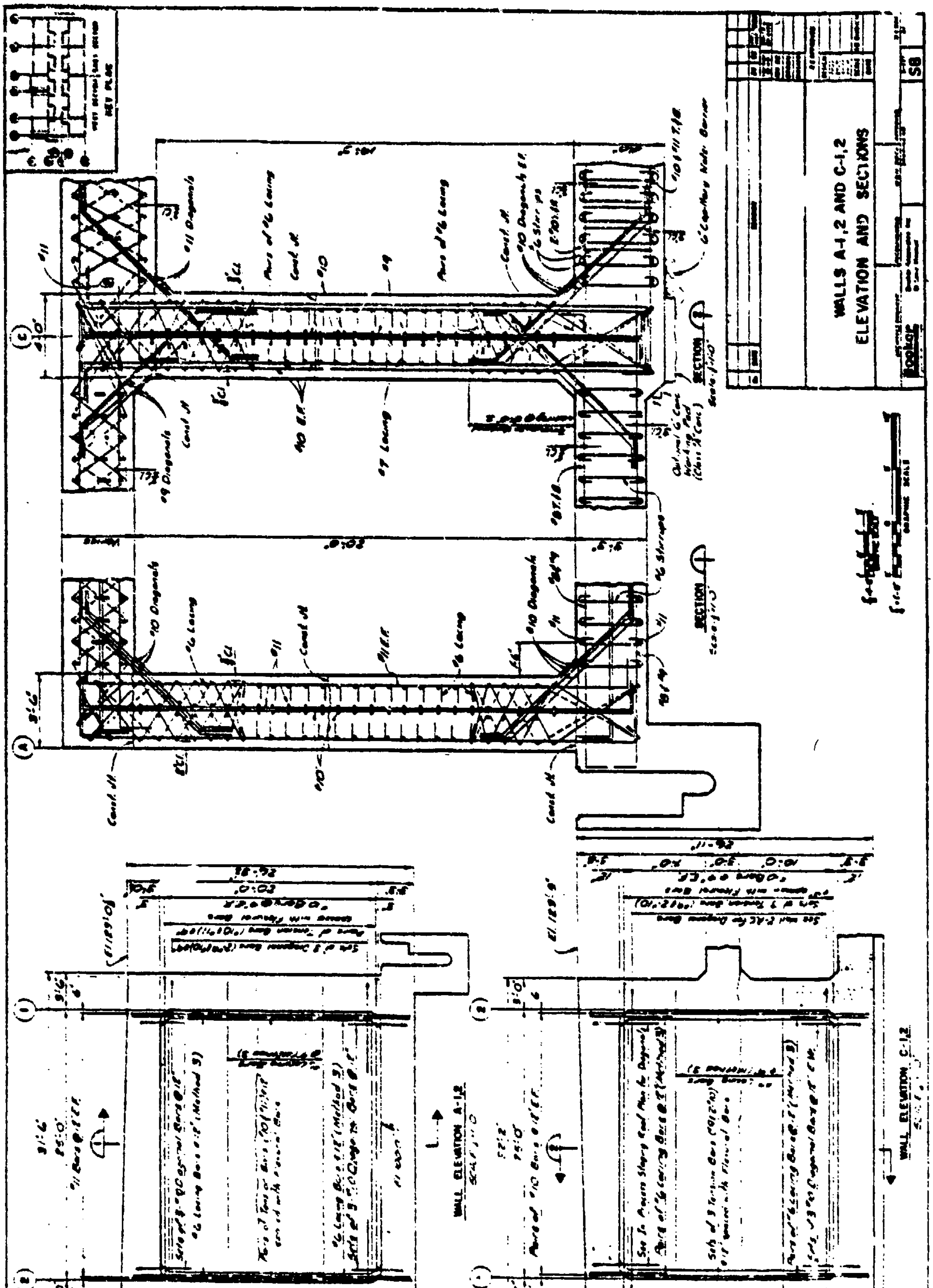
WALLS A-1,2 AND C-1,2
ELEVATION AND SECTIONS
WALL ELEVATION A-1,2
WALL ELEVATION C-1,2
SECTION
SECTION
GRAPHIC SCALE
SB

FIGURE No. 1

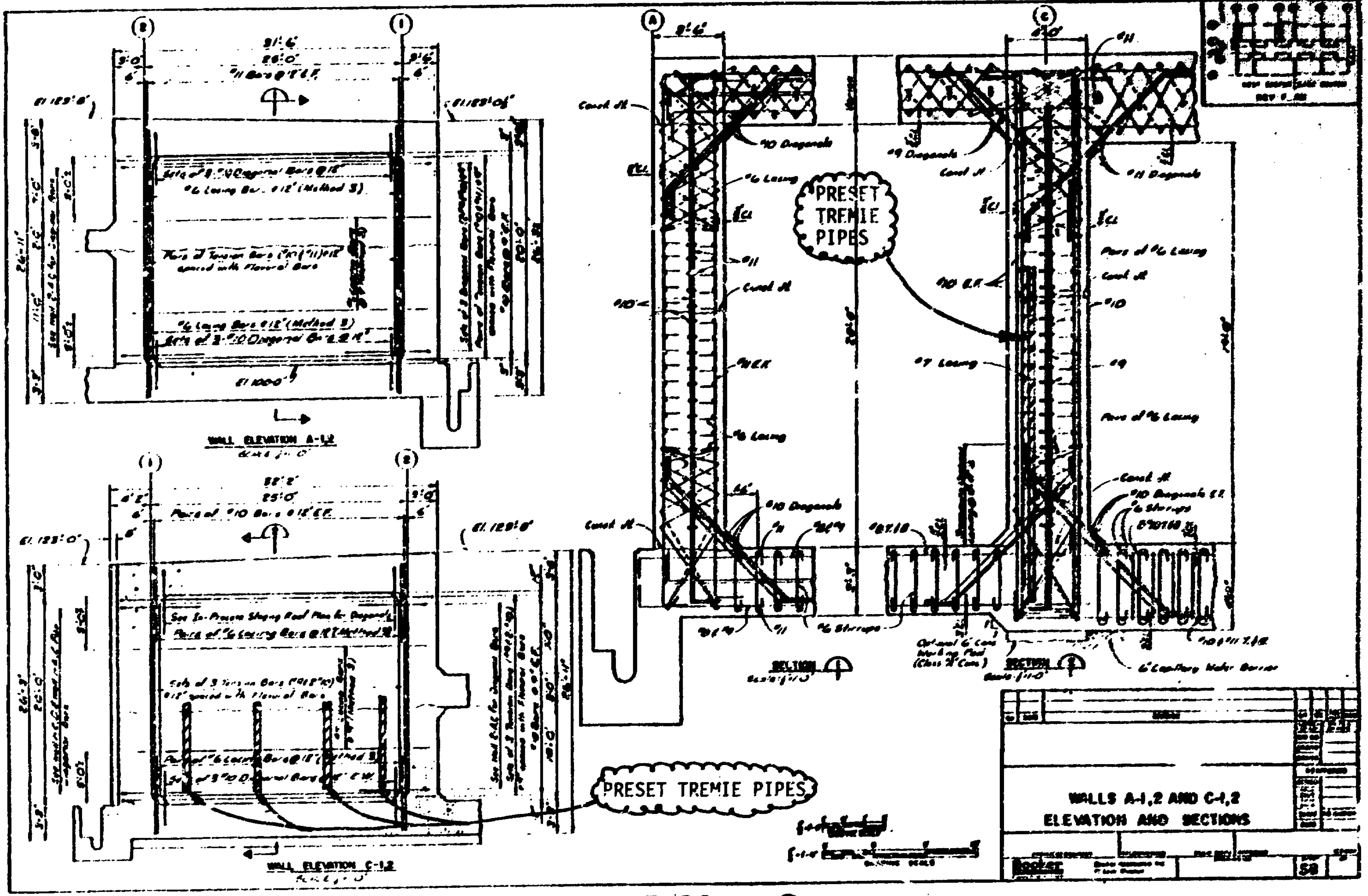
PRESET TREMIE PIPES
PRESET TREMIE PIPES
WALL ELEVATION A-1,2
WALL ELEVATION C-1,2
SECTION
SECTION
WALLS A-1,2 AND C-1,2
ELEVATION AND SECTIONS
A
C
1
2
#11 Bars @ 9" E.F.
#10 Diagonals
#9 Diagonals
#11 Diagonals
#6 Lacing
#7 Lacing
Pairs of #6 Lacing
#6 Stirrups
6" Capillary Water Barrier
SB

FIGURE No. 2

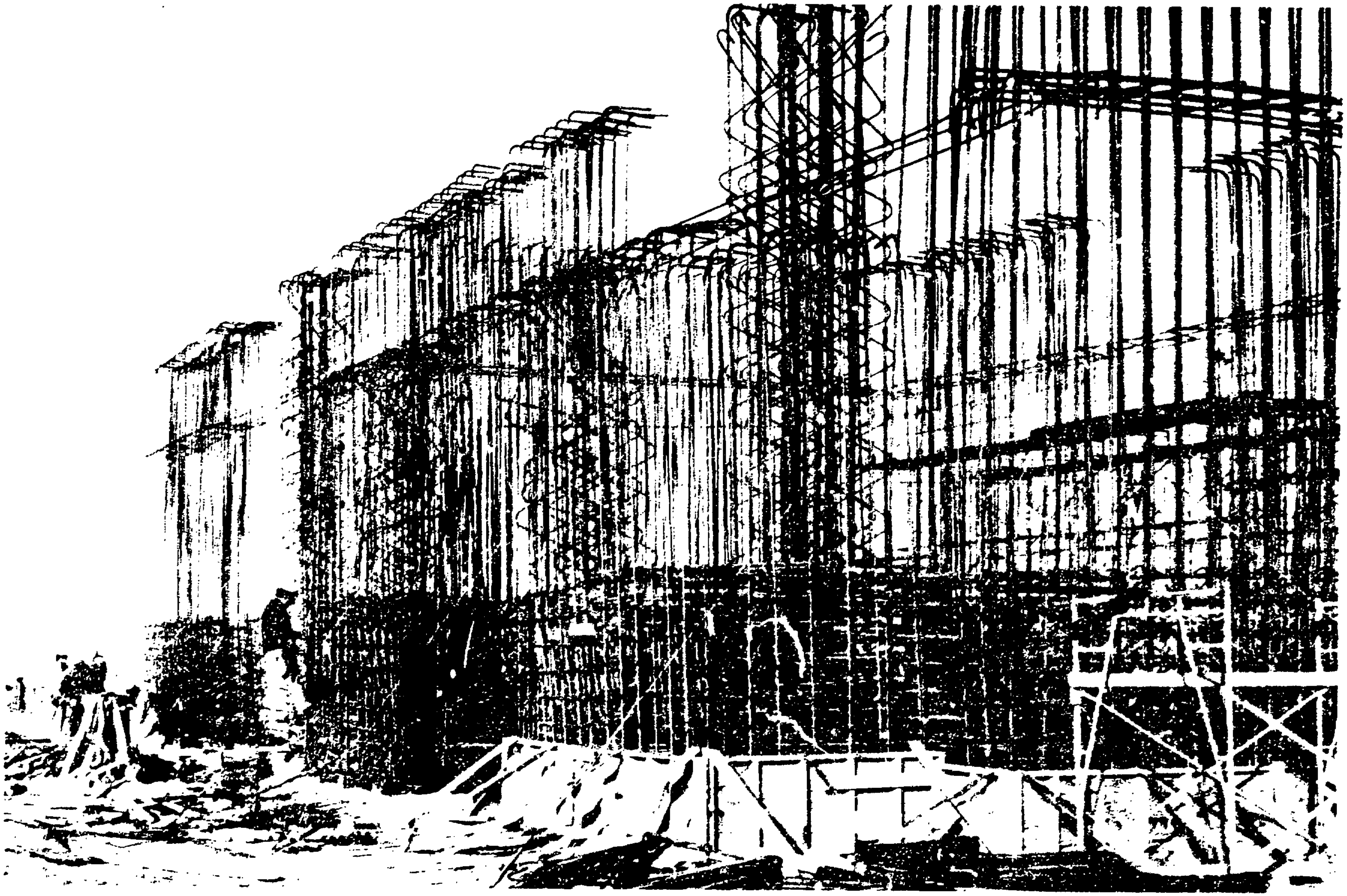

PHOTO No. 1

PHOTO No. 2

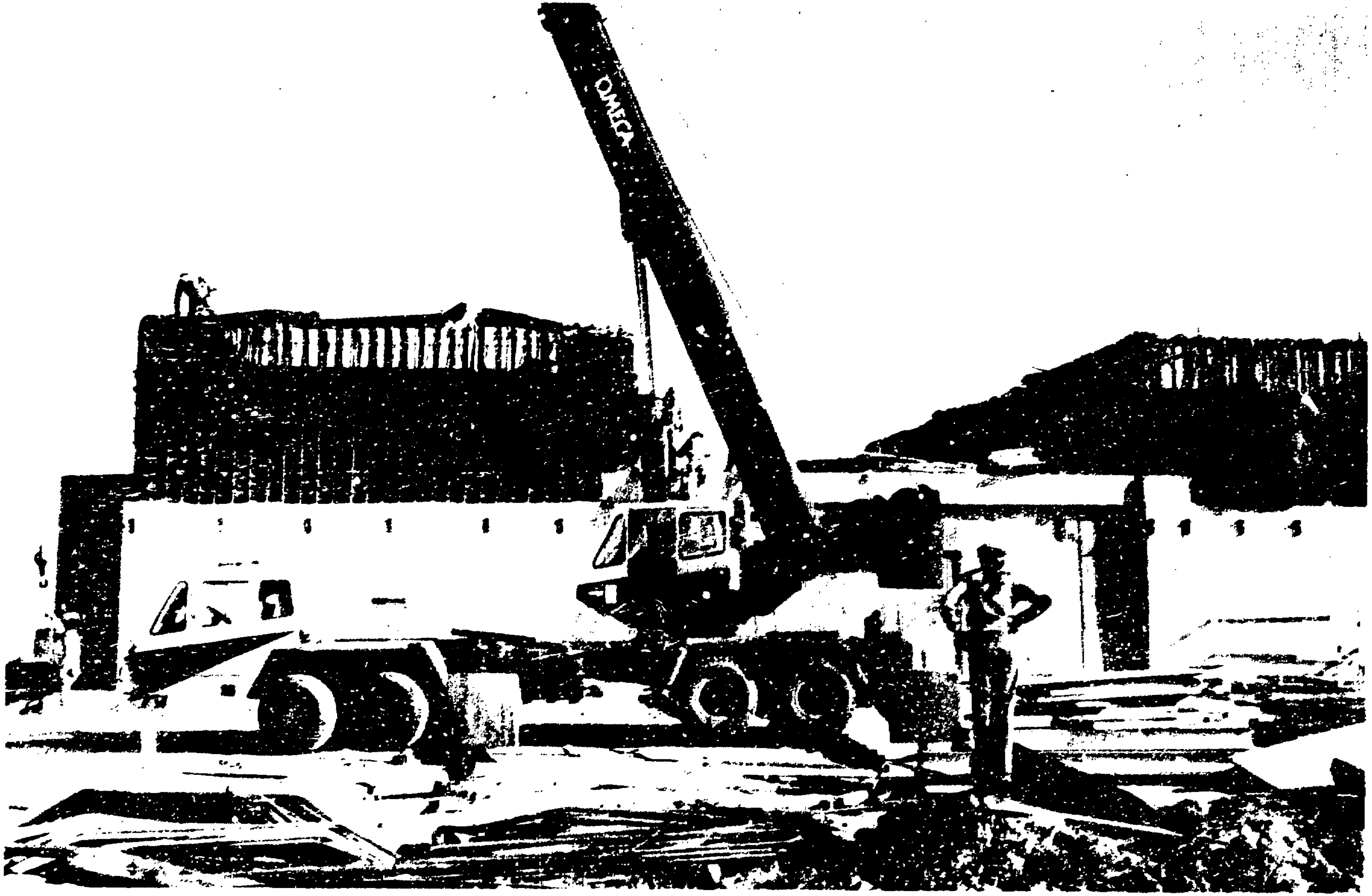

PHOTO No. 3

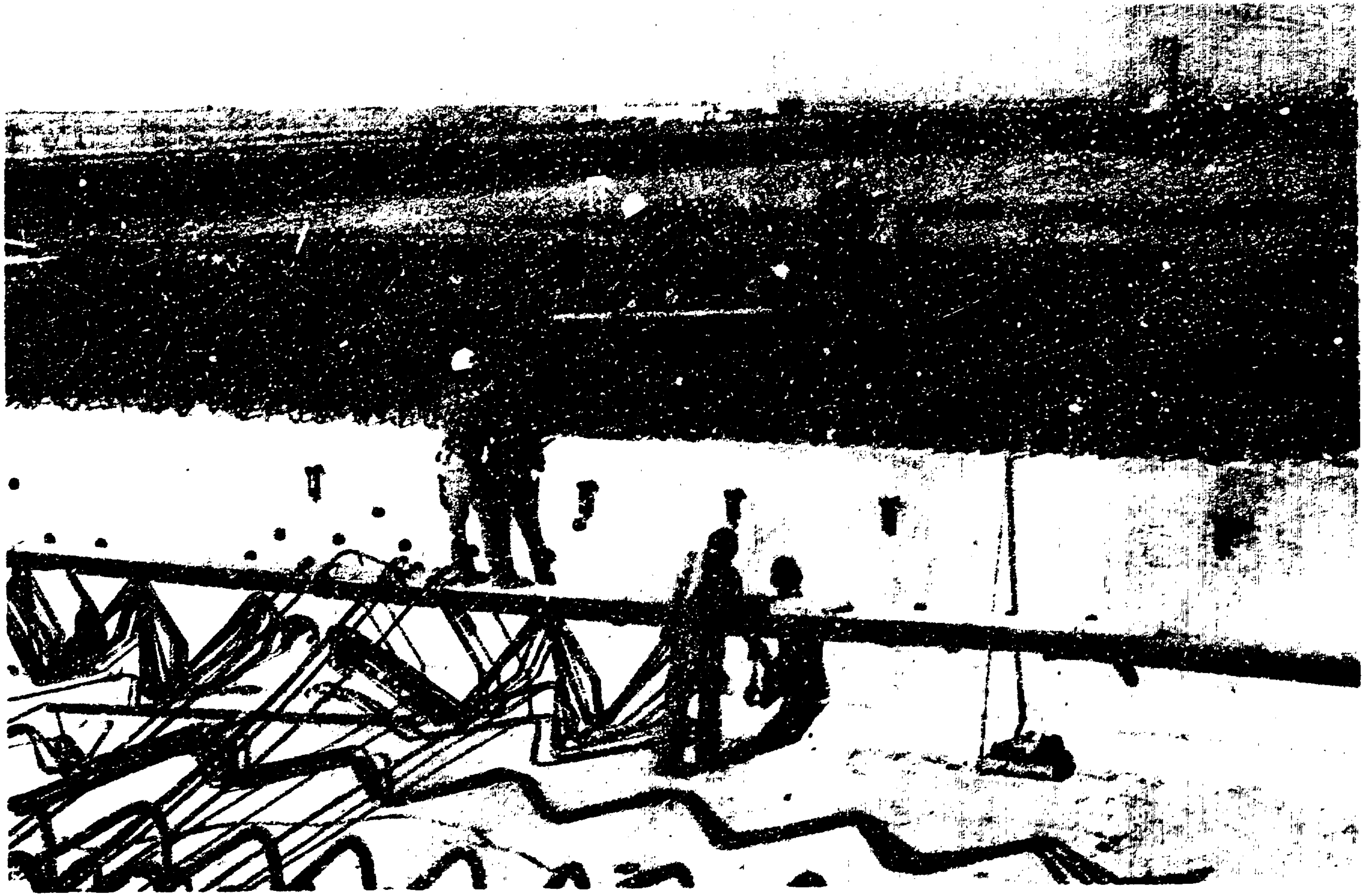

PHOTO No. 4

EFFECTS OF STIRRUP DETAILS ON LOAD-RESPONSE BEHAVIOR OF SLABS

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ABSTRACT

Ten one-way reinforced concrete slabs were tested, primarily to investigate the effects of shear stirrups and stirrup details on the load-response behavior of the slabs. The slabs were rigidly restrained at the supports and were loaded with a uniformly distributed pressure. Support rotations between 13 and 21 degrees were observed. The test series was unique due to the uniform loading and the large support rotations experienced for the conventionally reinforced concrete one-way slabs. The results of these tests indicate that criteria on shear reinforcement found in current blast-resistant design manuals are overly conservative.

INTRODUCTION

The test series discussed was a part of the Keyworker Blast Shelter Research Program conducted at the U.S. Army Engineer Waterways Experiment Station (WES) and sponsored by the Federal Emergency Management Agency (FEMA). At the time this study was initiated, civil defense planning called for the evacuation of nonessential personnel to safe (low-risk) host areas when a nuclear crisis is probable and the construction of blast shelters to protect the key workers remaining in the high-risk areas. Structural designs for 150-psi shelters with capacities between 100 and 400 people were developed. The results of this study significantly influenced the design of the blast shelter's roof slab, resulting in a more cost-efficient design.

Woodson [1] reviewed past research on testing one-way slabs and beams and found that experimental research using uniformly loaded beams or one-way slabs is very limited. Kiger and others [2] and Keenan [3] each tested one surface-flush, restrained one-way slab with a slowly increasing, uniformly distributed load. The slab tested by Kiger was one of a series investigating the effects of soil cover on the static and dynamic capacity of earth-covered slabs. The slab tested by Keenan was one of a series investigating the behavior of laced reinforced concrete slabs subjected to static and dynamic loads. Keenan's test series also included three restrained one-way slabs tested under short-duration dynamic loads and the results indicated that structural response modes were similar for static and dynamic loading.

The slab tested by Kiger contained 0.25 percent shear reinforcement in the form of closed rectangular hoops. The slab was loaded to collapse at a support rotation of approximately 20 degrees. Keenan's slab contained diagonal lacing bars that were bent around the exterior face of the transverse reinforcement in a grid system. The principal tension and compression reinforcement were placed to the interior of the transverse reinforcement. Safety limitations of the loading device prohibited testing of the slab to collapse. and the support rotation measured at test termination was approximately 9.2 degrees.

Based on point-loaded beam tests reviewed by Woodson [1], numerous researchers agree that closed hoops help increase the ductility of a reinforced concrete member by confining the concrete core. Large support rotations were experienced in Kiger's slab test [2], possibly due to the use of closed hoops. Keenan [3] reported that the diagonal lacing bars confined the core and increased the ductility of his slab. Prior to this study, a thorough investigation of the rotation capacity of conventionally reinforced one-way slabs and of the effects of hoop or stirrup details on the rotation capacity was not available in the literature. The construction of slabs using lacing bars is labor-intensive and costly, and is not considered to be conventional construction practice. Considerable effort is also required to place closed hoops throughout a reinforced concrete slab. Because of the lack of research in this area, laced reinforcement, closed hoops, or closely spaced stirrups are usually recommended in blast-resistant design. A knowledge of the effects of stirrup details on slab behavior will help optimize one-way roof-slab designs for structural response and allow for more cost-effective designs.

OBJECTIVES

Three objectives of the study were to investigate the effects of the following parameters on the behavior of one-way reinforced concrete slabs: (1) stirrup configurations as presented in Figure 1, (2) stirrup spacing, and (3) the interaction of the stirrups with the two principal reinforcement bar spacings shown in Figure 2. Types I, II, and III stirrup configurations consisted of a U-shaped double-leg stirrup with 135-degree bends on the ends, a single-leg stirrup with 135-degree bends on each end, and a single-leg stirrup with a 135-degree bend on one end and a 90-degree bend on the other end, respectively. An analysis based on three empirical relations for rotational capacity was used to determine the stirrup spacings to be investigated. The relations were derived from point-loaded beam tests and will be discussed in this paper. Stirrup spacings of 0.75, 1.5, and 3.0 inches were selected with the anticipation that the behavior of the slabs with the 0.75-inch spacings would be considerably different from slabs with the 1.5- or 3.0-inch spacings. A slab without stirrups was also tested. Two principal steel spacings, 1.75 and 3.75 inches, were used to investigate the criterion given by Keenan and others [4] that restricts the bar spacing to a value less than the effective depth, 1.9 inches.

SCOPE

Ten slabs were tested under a slowly increasing uniform load in the Small Blast Load Generator (SBLG) test facility at WES. All slabs were 24 inches wide by 36 inches long with a clear span of 24 inches and a thickness of 2.3 inches. Grade 60 deformed wire and 4,000-psi design strength concrete were used. The slabs had span-to-effective-depth ratios of about 12, and principal reinforcement ratios were about 0.008 in each face. Transverse (temperature) reinforcement was spaced at 3 inches on-center to the interior of the principal reinforcement in each face. In slabs having stirrups spaced at 3 inches, the combination of temperature steel and stirrups (particularly Type I stirrups) resembled a closed hoop. Each slab was instrumented for strain, displacement, and pressure measurements. Table 1 presents the construction parameters varied in this study for each slab.

The reaction structure used in the test series is shown in Figure 3. The slabs were clamped to the threaded rods to prevent rotation and translation. Figure 4 shows the test chamber, which consists of a series of stacked rings with a 3-foot 10-3/4 inch inside diameter and an elliptical dome top called a "bonnet." Static pressures of up to 500 psi can be generated by forcing water in the bonnet to load the test specimen. A waterproof membrane is used to separate the water from the test specimen.

RESULTS AND DISCUSSION

Figure 5 is a posttest view of the underside of the stirrup slabs. In general, the slabs responded in flexure in a three-hinged mechanism. The ultimate load resistance of the slabs was approximately 1.4 to 1.7 times the yield-line value. Compressive membrane theory closely predicted the ultimate load resistance of the slabs. The load-deflection curve in the tensile membrane region initially followed the slope derived from criteria by Park [5] in most slabs, but rupture of principal reinforcement prevented pure tensile membrane behavior from developing. The degree of a combined bending and tensile membrane response varied among slabs depending on stirrup details.

Figures 6, 7, and 8, respectively, present the midspan load-deflection data for stirrup Slabs 1 (no stirrups), 2 (closest stirrup spacing), and 8 (double-leg stirrup configuration). The effects of stirrup spacing were less in slabs with the 1.75-inch principal steel spacing than in slabs with the 3.75-inch spacing. The greatest tendency for tensile membrane behavior among the slabs with the 3.75-inch principal steel spacing was observed in Slab 2. Stirrups were spaced at 0.75 inch in Slab 2, and the load-carrying capacity in the tensile membrane region reached a value equivalent to the ultimate resistance. The principal steel spacing of 1.75 inches resulted in ductile behavior at stirrup spacings of 0.75 and 1.5 inches. The slab having Type I stirrups (Slab 8) experienced slightly greater tensile membrane tendencies than the slabs having Type II or Type III stirrups. No significant difference was observed in the behavior of slabs with Type II and Type III stirrups.

The rotation of the hinges at the supports when the tests were terminated (anticipated incipient collapse) are presented in Table 2. Table 2 also gives the percentage ratio of maximum attained midspan deflection (Δ_{max}) to the clear span length (L). The rotation capacity of the plastic hinges is directly related to the ductility of the slab. Figure 9 presents the results of calculations using empirical relations developed from beam tests by Corley [6], Mattock [7], and Baker and Amarakone [8] for plastic hinge rotation. The significance of Figure 9 is that it shows an increase in rotation capacity when closely spaced stirrups are used. The vertical dashed lines in Figure 9 indicate the spacings used in this test series. The empirical expressions are for design purposes and tend to be conservative. Corley's relation yields a value of approximately 4.8 degrees for plastic hinge rotation in the slab with a 0.75-inch stirrup spacing.

Based on beam test data, Keenan and others [4] state that reinforced concrete members with compression steel can reliably maintain their ultimate moment resistance to support rotations of up to 4 degrees, provided the compression bars are confined by effective ties and q $\leq$ 0.14 where q is the reinforcing index defined by:

$$q = \frac{(\rho f_y - \rho' f_y')}{f_c'}$$

where

ρ = tension steel ratio

f_y = yield strength of tension steel

ρ' = compression steel ratio

f_y' = yield strength of compression steel

f_c' = compressive strength of concrete

Assuming the stirrups act as effective ties, the slabs in this test series meet Keenan's criterion, except for the slab without stirrups. Keenan states that if the slab is laterally restrained, deflection of the member induces membrane forces and the member may develop substantial resistance to maximum support rotations exceeding 12 degrees. Another design manual for blast-resistant structures [9] requires that stirrups be spaced a distance not greater than one-fourth the effective depth of the slab when inelastic response is predicted. Slab 1 contained no stirrups and maintained its yield-line resistance of about 42 psi up to support rotations of approximately 16.3 degrees. The results of these tests indicate that criteria concerning shear reinforcement in current blast-resistant design manuals are overly conservative and should be revised.

SUMMARY AND CONCLUSIONS

Ten one-way reinforced concrete slabs were statically tested under a uniform load to large deflections. The effects of stirrups on the load-response behavior of roof-slabs were investigated. Results indicate that ductile behavior is increased by construction details that help confine the concrete core of the slab (i.e., closely spaced stirrups, Type I stirrups, and closely spaced principal reinforcing bars). However, the increase in ductility of one-way slabs resulting from special reinforcement details does not, in general, justify the expense of the special details. For example, single-leg stirrups were nearly as effective as double-leg stirrups in contributing to ductile behavior. Closely spaced single-leg stirrups were effective in significantly improving the ductility of the slab, indicating that closed hoops are not needed. Spacing the principal reinforcing bars a distance less than the effective depth as recommended by Keenan and others [4] did improve the ductility of the slab and is a relatively cost-effective construction requirement.

A major contribution of this test series to the state-of-the-art in blast-resistant structural design is the finding that a conventionally reinforced, restrained one-way slab without stirrups or ties can maintain its yield-line resistance up to support rotations exceeding 16 degrees. The results of these tests indicate that criteria on shear reinforcement found in current blast-resistant design manuals are overly conservative. The data show that laced reinforcement, closed hoops, or closely spaced stirrups are not necessary to induce a ductile response with large support rotations in one-way roof slabs.

ACKNOWLEDGMENTS

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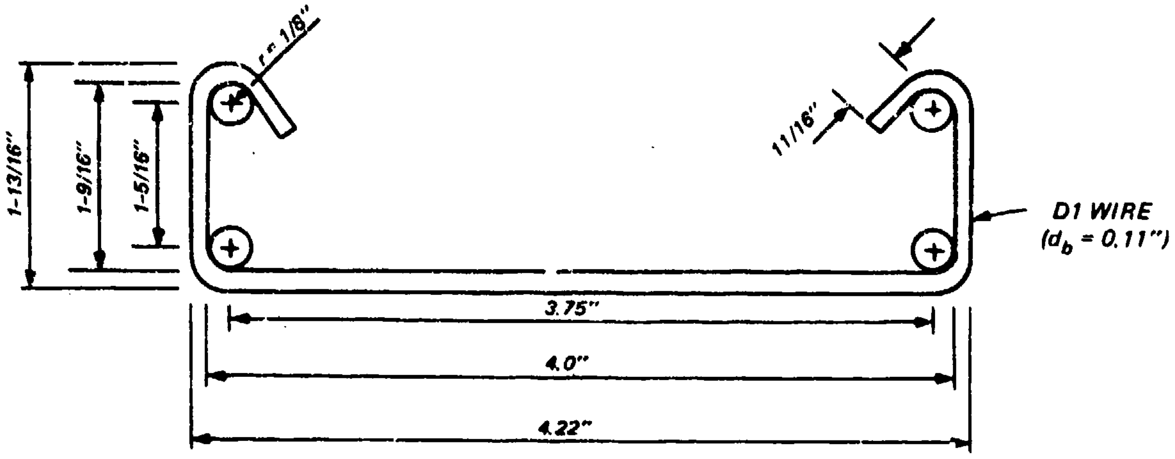
Table 1. Slab Characteristics.

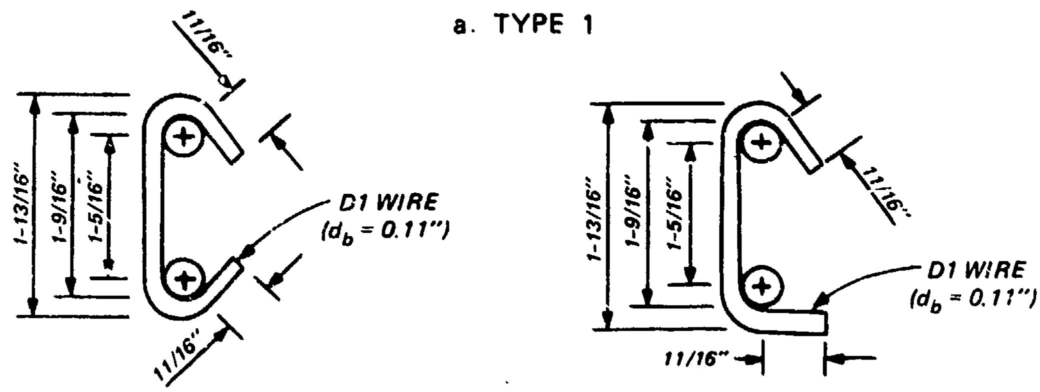
Slab	Stirrup Configuration Type	Stirrup Spacing in.	Principal Steel Spacing in.
1	No Stirrups	--	3.75
2	II	0.75	3.75
3	II	1.5	3.75
4	II	3.0	3.75
5	II	1.5	3.75
6	III	1.5	3.75
7	III	1.5	3.75
8	I	1.5	3.75
9	II	1.5	1.75
10	II	0.75	1.75

Table 2. Maximum Support Rotations.

Slab	Rotation degrees	$\frac{\Delta_{max}}{L}$ percent
1	16.3	14.6
2	20.6	18.8
3	14.0	12.5
4	13.1	11.7
5	15.4	13.8
6	14.0	12.5
7	14.5	12.9
8	14.0	12.5
9	16.3	14.6
10	18.4	16.7



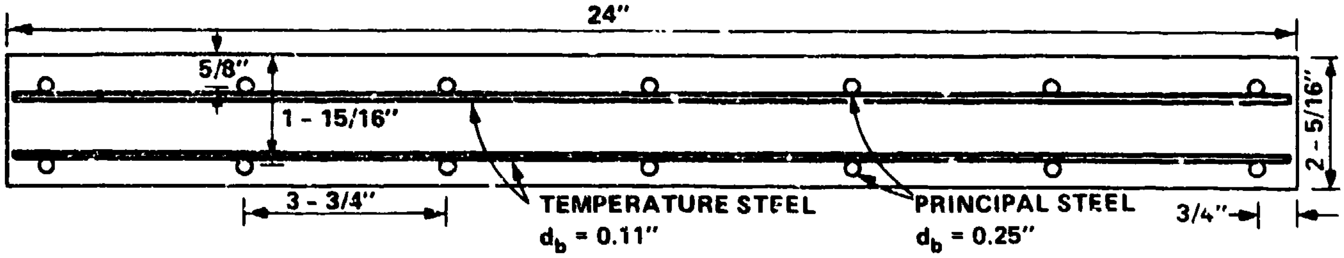
a. TYPE 1



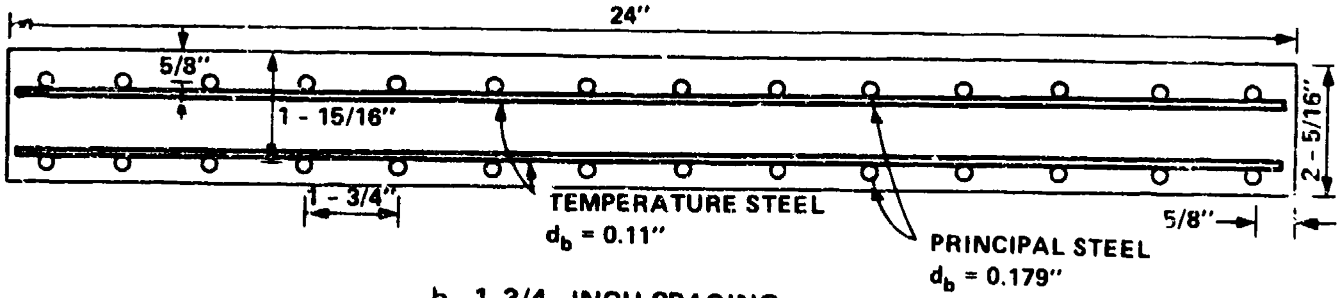
b. TYPE 2

c. TYPE 3

Figure 1. Stirrup Details.



a. 3-3/4- INCH SPACING



b. 1-3/4- INCH SPACING

Figure 2. Principal Reinforcement Details.

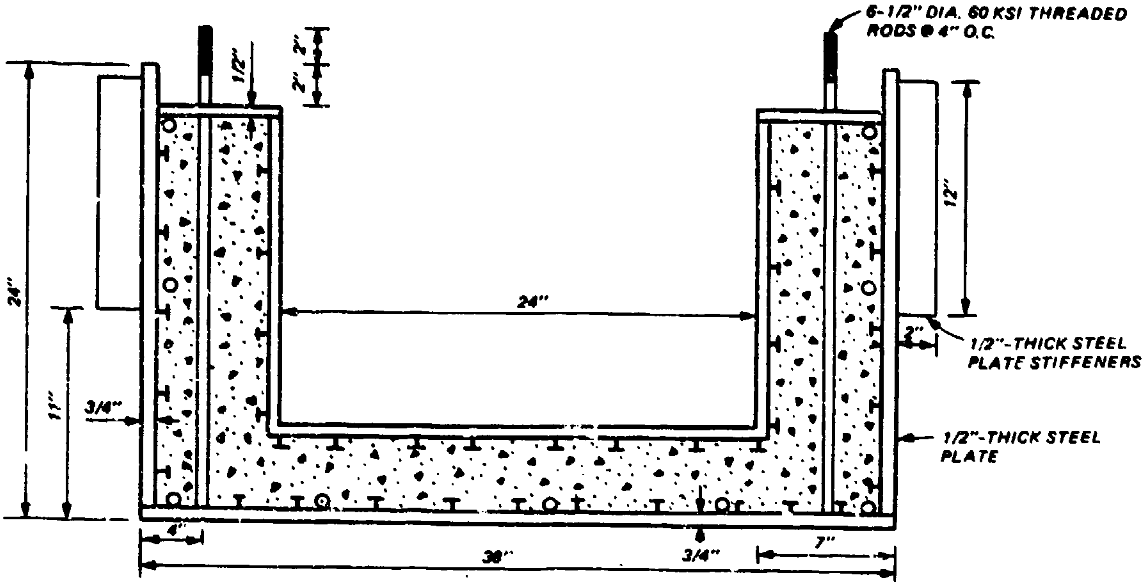

6-1/2" DIA. 60 KSI THREADED RODS @ 4" O.C.
1/2"
2" 2"
24"
12"
24"
2"
1/2"-THICK STEEL PLATE STIFFENERS
11"
3/4"
1/2"-THICK STEEL PLATE
4"
38"
3/4"
7"

Figure 3. Cross Section of Reaction Structure.

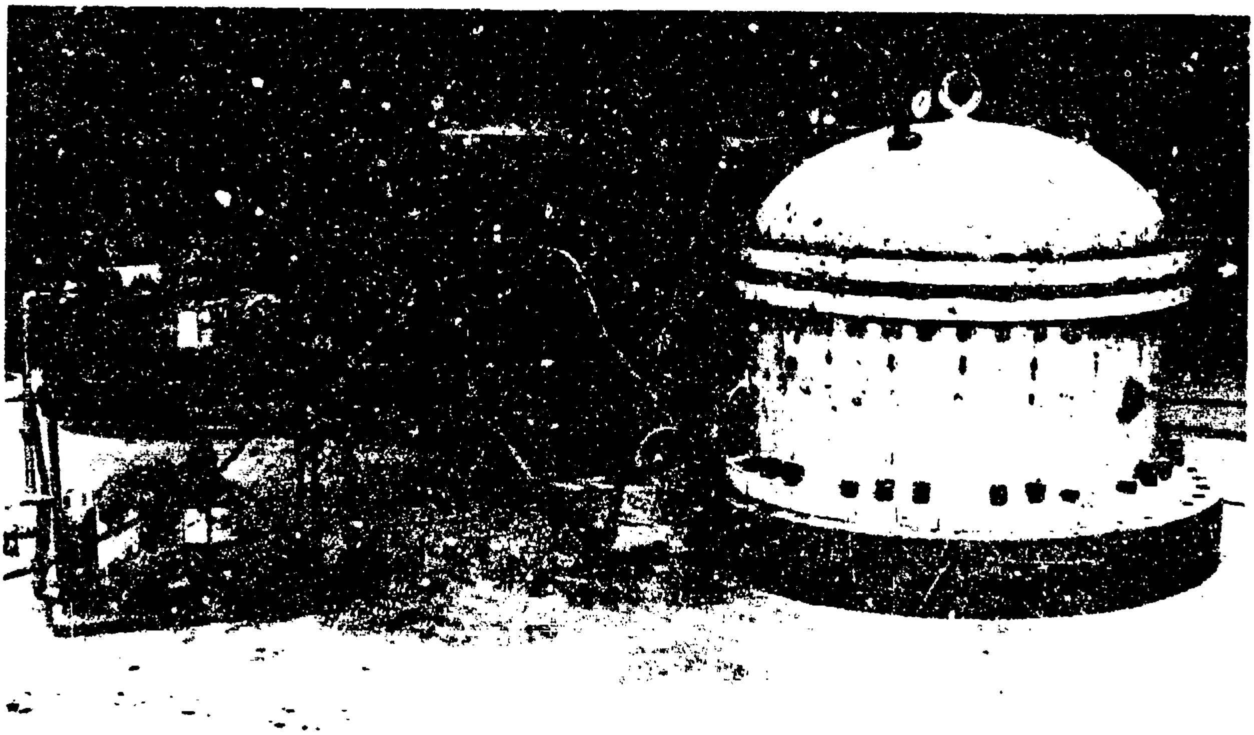


Figure 4. Test Chamber.

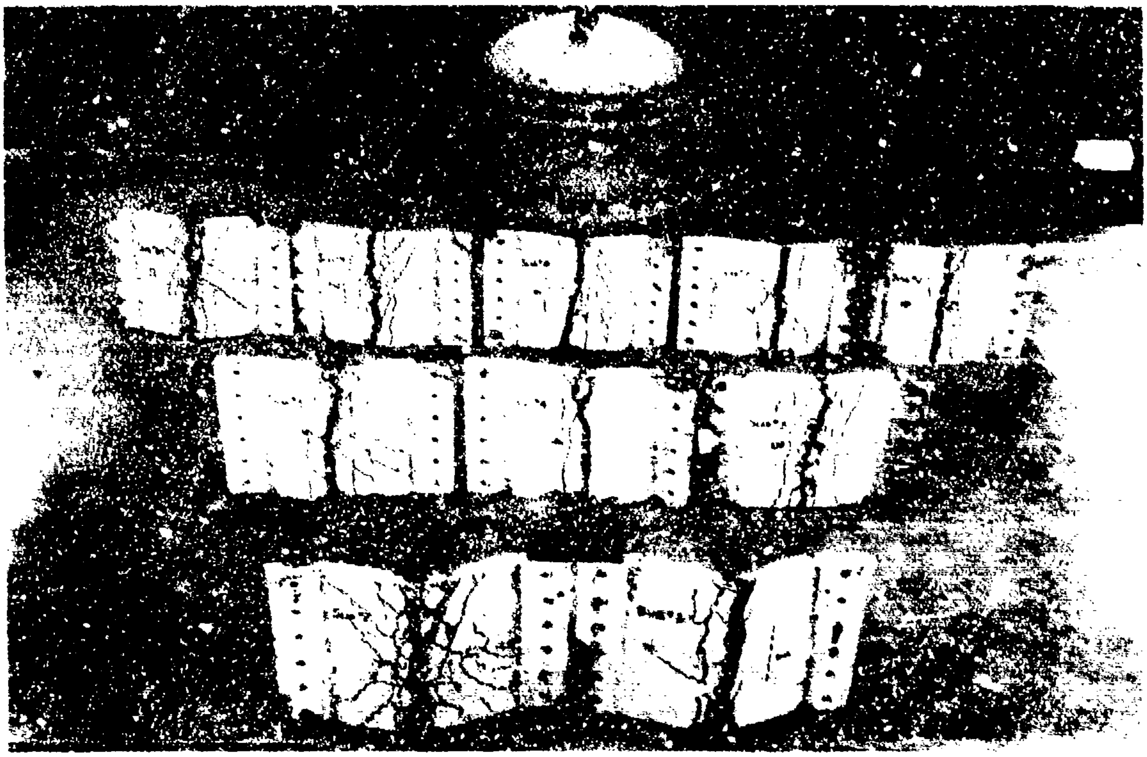


Figure 5. Posttest View.

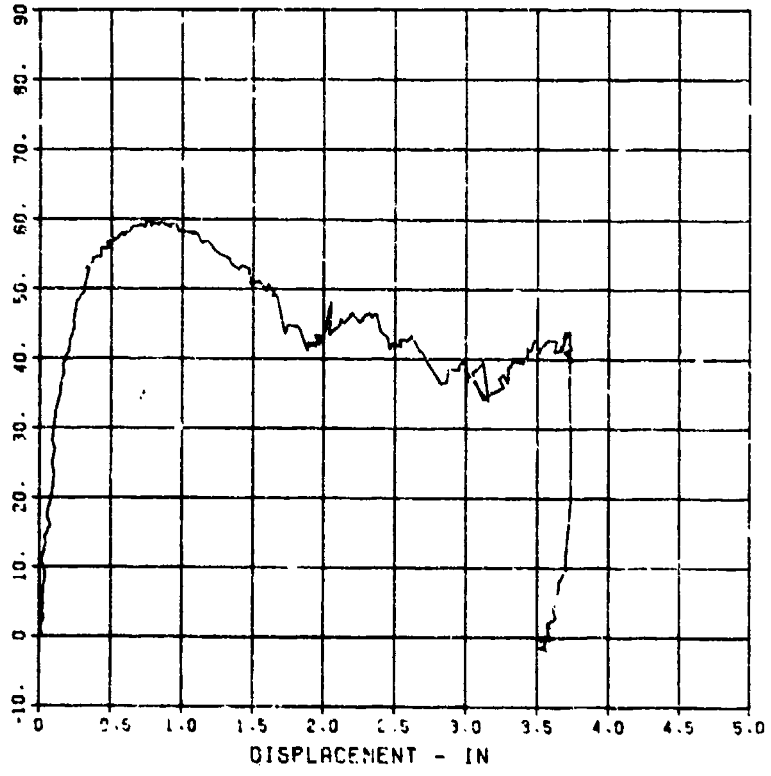


Figure 6. Slab 1 Midspan Load-Deflection Curve.

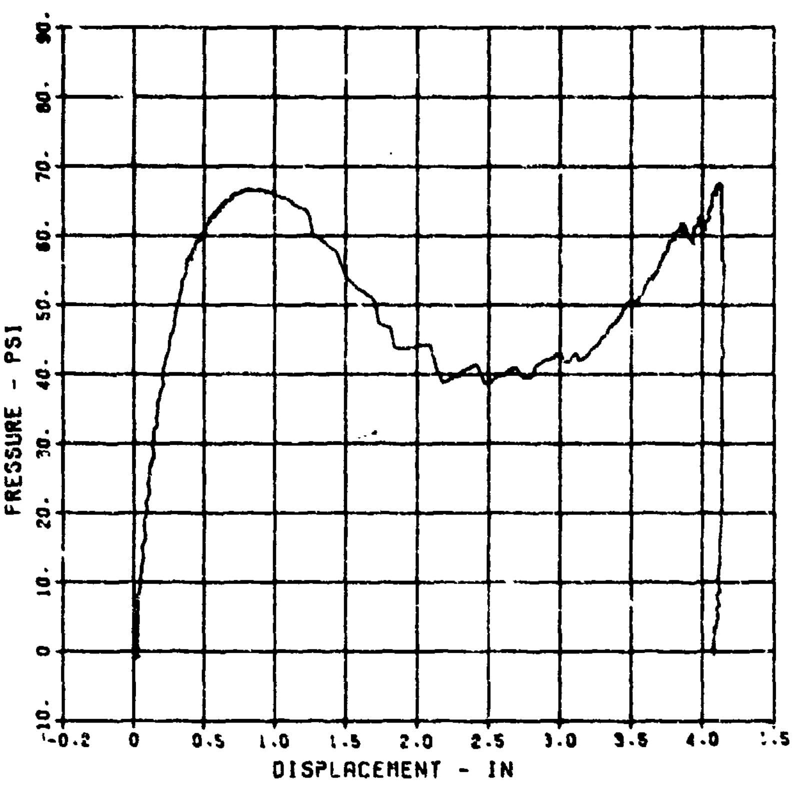


Figure 7. Slab 2 Midspan Load-Deflection Curve.

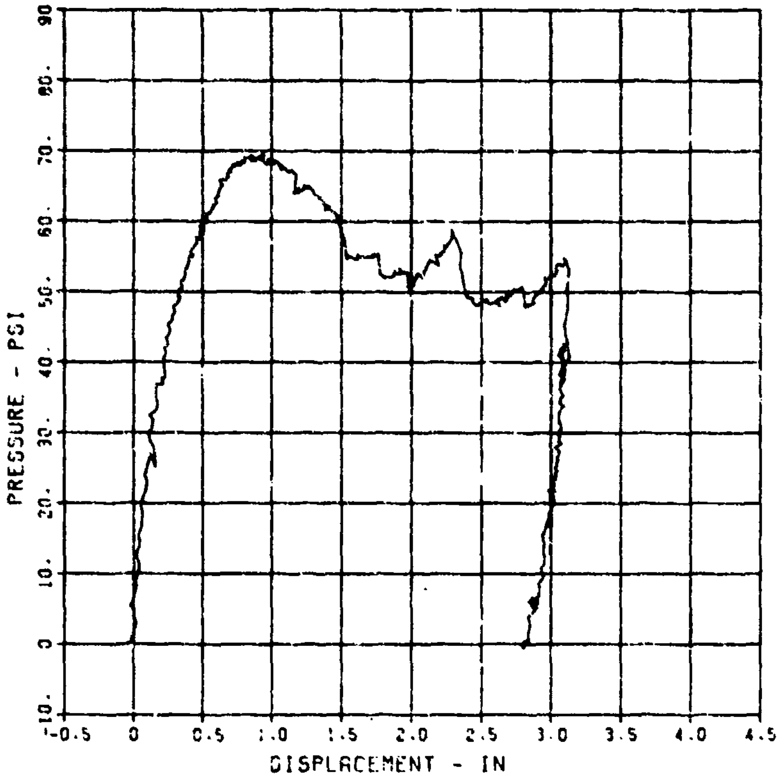


Figure 8. Slab 8 Midspan Load-Deflection Curve.

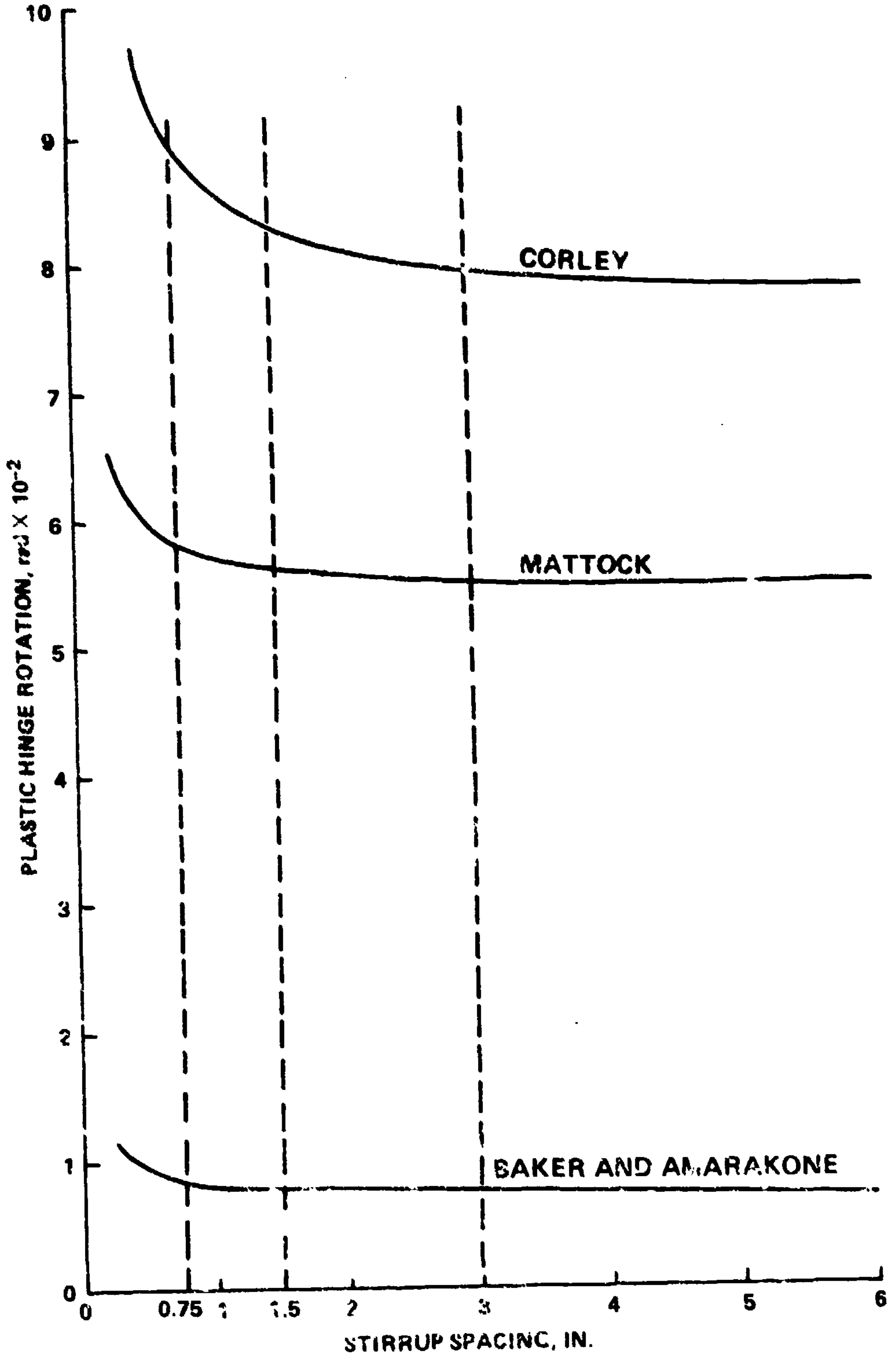


Figure 9. Rotation Capacity Versus Stirrup Spacing.

IMPROVED MIXING, GRANULATION AND DRYING OF HIGHLY ENERGETIC PYROMIXTURES

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ABSTRACT

A safer and more efficient method of mixing, granulating and drying (MIGRAD) highly energetic (UN 1.1) pyrotechnic composition will be reported. The process uses a MIGRAD mixer/granulator that was tailored to mix, granulate and dry a pyrotechnic material (20-40 lbs.) within a single mixing chamber. Features of the process include remote loading and unloading, reduced solvent, shortened mixing cycle (40 minutes), infinitely variable speed control of mixing and granulating impellers, built-in state-of-the-art fire detection/ suppression (UV-50MS, IR-10MS), explosion venting, heated-chamber, vacuum drying, remote/ programmable controls, and remote mixer cleanup using energy of the mixer. The mixing process will be evaluated for preparation of some 24 pyrotechnic compositions for five Arsenals/Ammo Loading Plants. Hazards Classification Safety Data Sheets were prepared for the 24 pyrotechnic compositions and will be reported along with resultant physical properties of the completed compositions.

INTRODUCTION

Manufacturing Methods and Technology Project 582/3T09: Improved Processing of Pyromixtures, was funded by the Munitions Production Base Modernization Agency to develop better and safer ways to prepare Class 1.1 pyrotechnic mixtures. Project responsibility was assigned to Pine Bluff Arsenal, with the technology developed to be shared with the four other installations within the Army's Armament, Munitions and Chemical Command who manufacture pyrotechnic munitions. These installations are Longhorn Army Ammunition Plant, Lone Star Army Ammunition Plant, Lake City Army Ammunition Plant and Crane Army Ammunition Activity. The new manufacturing technology is to be implemented thru modernization projects at the five installations, to assure safer and better manufacturing procedures for highly energetic pyromixtures.

DISCUSSION

DEFINITION OF THE PROBLEM

A fact finding trip was made to each of the five installations engaged in production of pyrotechnic munitions. Although the pyromixtures made at each plant are generally different, the similarity of problems at the five plants was surprising. The basic problem was too much exposure of operators to the hazards of pyromixture production due to the multiple processing steps involved. Typical processing steps follow:

1. Load raw materials into mixer
2. Mix the pyromixtures
3. Unload mixer and manually load granulator
4. Granulate pyromixture
5. Manually load pyromixture into dryer
6. Manually unload dryer

With the basic problems identified, a set of project goals was established. (Figure 1)

MIXER SELECTION

A search was conducted to identify a mixer that would ensure proper mixing, granulation and vacuum drying of pyrotechnic powders and lend itself to restructuring/tailoring for accomplishment of project goals. The mixer selected was the 30 liter brandy glass shaped "Dry Disperser Mixer/Granulator" made by Baker-Perkins Chemical Machinery Ltd., a British firm. The mixer was marketed in the United States by Jaygo, Inc. The basic mixer is shown in Figure 2. The mixer has two hydraulically driven impellers. Mixing is accomplished by the mixing impeller located in the bottom of the mixer, while granulation is achieved by the granulating impeller, or chopper, located in the side of the mixer. The hydraulic motors drive the impellers in infinitely variable speeds from 0-650 RPM (mixer) and 0-1000 (chopper). The mixing bowl is jacketed to permit cooling or heating and should meet ASME VIII, Division I (internal working pressure 170 psig). The mixer is equipped with a hydraulically activated discharge valve that allows automatic and remote unloading of the mixer.

Auxiliary equipment was added, as show in Figure 3, to permit accomplishment of project goals. Auxiliary equipment consisted of the following:

1. A mixer extension with entry ports for adding dry raw materials, liquid binders, and deluge water.
2. A rupture disc (10 psi rated) to close the mixer.
3. A vent stack to vent any unsuppressed fire.
4. Powder dumpers and hopper for remote raw material loading.
5. Hot and chilled water circulation systems for bowl heating/cooling.
6. A vacuum pump and refrigerated vapor condenser to remove and collect solvent.
7. Temperature sensors to measure temperature of the product and the air above the product.
8. Piping/valving for mixer washdown and cleanup.

Finally, a fire detection/suppression system was added to achieve the fastest possible response time (10-50 ms) in the event of a fire. The complete mixer with built in fire detection system is shown in Figure 4. The fire detection sensors consist of infrared radiation sensor, pressure sensor (4 psi rated) and temperature (210°F/99°C rated) installed directly in the mixer extension. Ultraviolet radiation sensors monitor the operating bay and the vent stack. Deluge water is delivered independently through a primac valve and preprimed deluge lines, and through a pressurized water storage reservoir and explosively actuated deluge valve located at the mixer.

MIXER CAPABILITIES

The mixer, as described above, performs three functions. It mixes, granulates and drys pyrotechnic mixtures within a single piece of equipment and without intermediate handling steps. This new mixing system was given the name MIGRAD System. MIGRAD is an acronym for MIxer-GRanulator-Dryer. Features of the mixer are listed in Figure 5.

Figure 6 lists the key mixing variables for the MIGRAD Process. Proper balance and control of these variables results in a well mixed, granular pyromixture. Consistency from batch to batch can be achieved by using a programmable controller to control the interrelationship of variables once the proper relationship has been extablished experimentally.

The steps in preparation of a typical pyromixture batch are shown in Figure 7. Figure 8 is a plot of temperature and vacuum vs. time for a typical inert starter mix batch. In this plot, dry mixing was accomplished at 50-60°F (10-16°C) for about 3 minutes at which time binder was added and granulation achieved about seven minutes into the cycle. Water at 150°F (65°C) was introduced to the mixer bowl jacket and vacuum at 20 in. Hg (252 MM Hg Abs) was started at the end of granulation. There was a rapid increase in product temperature and the air temperature above the product for the next five minutes. Vacuum was allowed to increase rapidly 12 minutes into to cycle. There was an immediate decrease in product temperature due to the cooling effect of the evaporating solvent (acetone). The product temperature reached its lowest point sixteen minutes into the cycle. Most of the solvent had been removed about 22 minutes into the cycle as evidenced by the vacuum level becoming constant at about 29 in. Hg (23 MM Hg Abs). Drying was complete when product temperature and air temperature above the product flattened out and the two temperatures were about 12°F (-11°C) apart. The volatile content was 0.02% and the granulation is shown in Figure 8. Figures 9 and 10 show batch data plots for typical Starter Mix XXV and Delay Mix VII Pyromixtures.

SAFETY CERTIFICATION TESTS

Tests to characterize the 24 pyromixtures used in the study were conducted at the Hazards Test Range located on the National Space Technology Laboratory grounds, NSTL, MS. Figure 11 shows the Hazards classification tests and full scale blending tests conducted on the 24 pyromixtures. Pyromixture safety data, which includes parametric, stability, sensitivity and output test results are reported in Table 1. Key safety data are reported in Table 2. Column 1 of this data shows the burning rate in sec/cm of loose pyromixture in a Vee Block test device. Pyromixtures with burn times less than 0.06 sec/cm should be treated with care and concern. Six pyromixtures had burning rates faster than 0.06 sec/cm. Column 2 lists electrical spark sensitivities in joules. Those pyromixtures that ignite with less than one joule of electrical energy are considered very sensitive to electrostatic charge. Four pyromixtures fell in the sensitive category. Column 3 lists impact sensitivities using the Bureau of Explosives test device. The 11 pyromixtures that exhibited a reaction at a drop height of 3.75 inches are considered impact sensitive. Column 4 presents friction sensitivity data generated on the Roto-friction device. Pyromixtures with Eq valves less than 100 ft - lb^2/sec are friction sensitive. Nine pyromixtures fell in the sensitive category. Column 5 lists pressure rates of rise in psi/sec. Those with readings greater than 200 psi per second build pressure at a rate that demands close examination of the venting system in case of an unexpected ignition and deluge system failure.

Based on these key safety data the Safety Consultant and Co-author, Mr. Fred McIntyre, has recommended against use of the MIGRAD System for four pyromixtures, for reasons as follows:

40MM Ignition Mixture - Fails all five tests (new ignition mixture is being developed)

Fuel Mix VI - Fails all except impact sensitivity test

IM-28 Incendiary Mixture - Fails all except electrostatic sensitivity test

M22 Flash Mixture - Pressure rate of rise exceeds mixer's ability to vent

The 24 pyromixture formulas are shown in Figure 12.

CONCLUSIONS

The MIGRAD System has design and construction characteristics that permit mixing, granulating and drying of a pyromixture within a single vessel. It has the capability for remote loading of raw materials into the mixer and remote discharge of the completed mix batch. It has a built-in fire detection system and tailor-made fire suppression system that represent the latest state-of-the-art in fire protection equipment. The system affords maximum operator protection.

Safety data characterizing the 24 pyromixtures to be used in the study provide the basis for decision making with regard to the on-going mixing process development studies.

- IMPROVE SAFETY
- ELIMINATE/REDUCE SOLVENT
- SHORTEN MIXING TIMES
- IMPROVE GRANULATION
- AUTOMATIC MIX DISCHARGE
- IMPROVE MIXER BOWL CLEANUP
- IMPROVE MATERIALS HANDLING
- IMPROVE FIRE DETECTION/SUPPRESSION

FIGURE 1: PROJECT GOALS

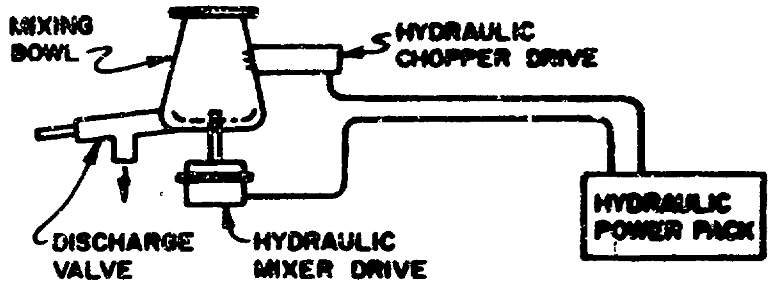

FIGURE 2: MIGRAD MIXER

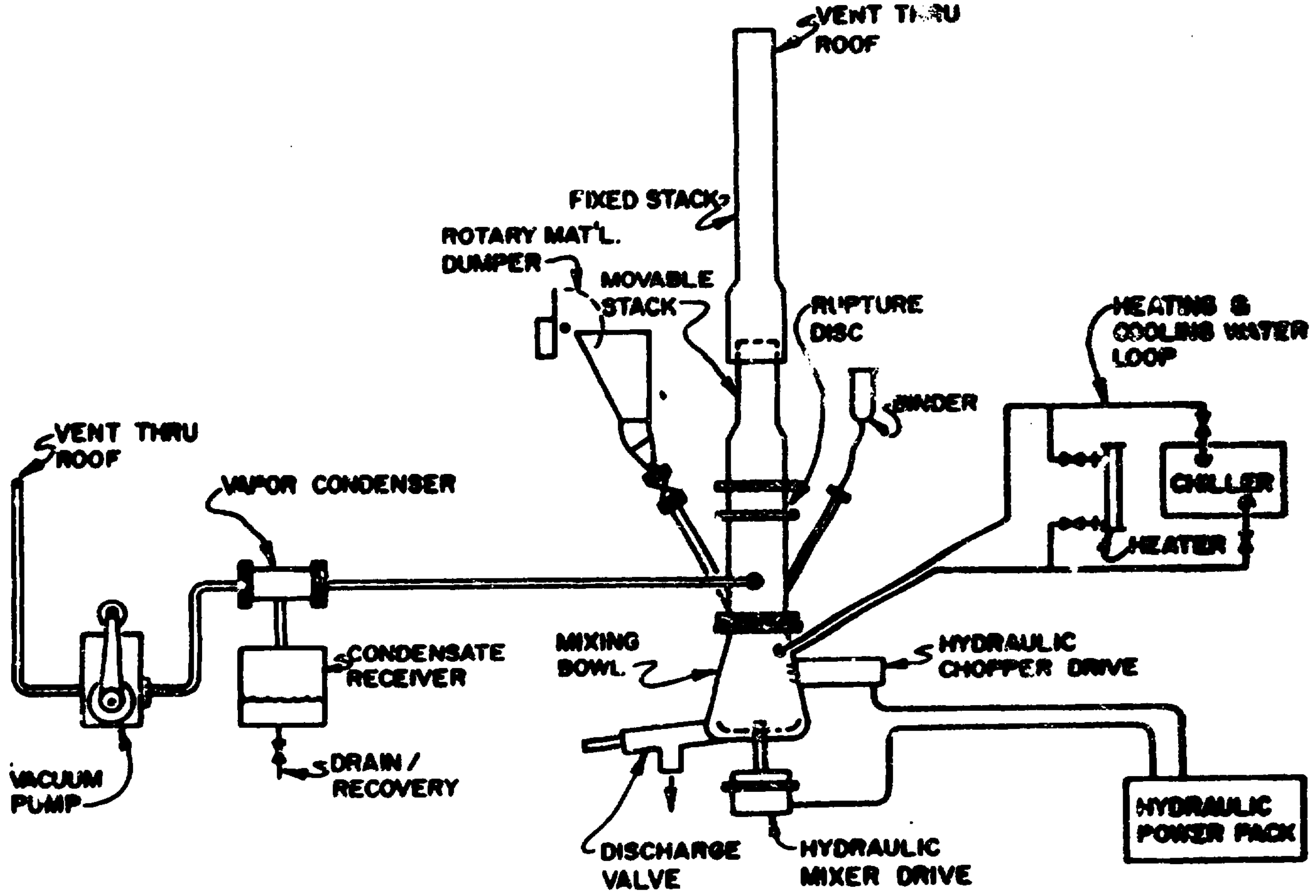

FIGURE 3: MIGRAD MIXER, MODIFIED FOR PYROTECHNICS

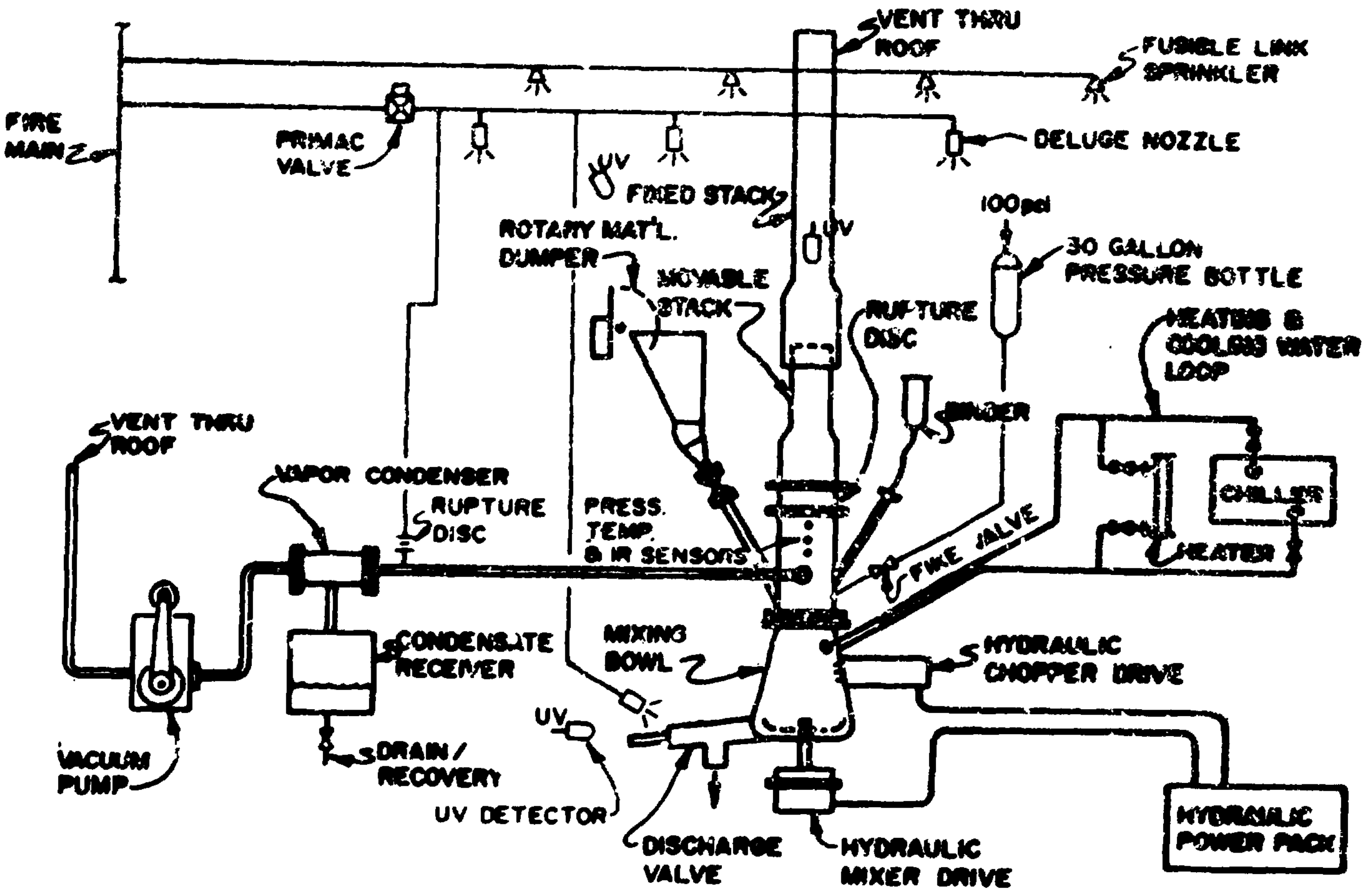

FIGURE 4: MIGRAD MIXER, MODIFIED FOR PYROTECHNICS, WITH FIRE PROTECTION

1. CLOSED OPERATION
2. SHORTENED MIXING CYCLES
3. REDUCED LEVELS OF SOLVENT
4. REMOTE LOADING OF RAW MATERIALS
5. REMOTE, AUTOMATIC UNLOADING OF PYROMIXTURE
6. HYDRAULICALLY DRIVEN MIXING & GRANULATING IMPELLERS
7. INFINITE SPEED CONTROL OF MIXING & GRANULATING IMPELLERS
8. BUILT-IN FIRE DETECTION/SUPPRESSION
9. FIRE/EXPLOSION VENTING TO ATMOSPHERE
10. JACKETTED BOWL FOR HEATING/COOLING
11. GRANULATION ACHIEVED WITHOUT SECONDARY OPERATION
12. VACUUM DRYING WITHIN MIXER
13. REMOTE, PROGRAMMABLE CONTROLS
14. REMOTE MIXER CLEANUP USING ENERGY OF MIXER

FIGURE 5: FEATURES OF THE MIGRAD MIXING SYSTEM

1. MIXING IMPELLER SPEED AND TIME
2. GRANULATING IMPELLER SPEED AND TIME
3. VOLUME OF SOLIDS
4. VOLUME OF SOLVENT
5. TEMPERATURE
6. VACUUM

FIGURE 6: KEY MIXING VARIABLES FOR MIGRAD PROCESS

1. PLACE PREWEIGHED RAW MATERIALS IN DUMPERS.
2. PLACE BINDER IN BINDER TANK
3. REMOTELY LOAD RAW MATERIALS INTO MIXER (DUMPERS PLACE RAW MATERIALS INTO FEEDER HOPPER)
4. DRY BLEND THE RAW MATERIALS FOR 3 MINUTES (UNLESS SAFETY CONCERNS PROHIBIT DRY BLENDING)
5. ADD BINDER AND RUN CHOPPER TO ACHIEVE GRANULATION
6. INTRODUCE HOT WATER INTO MIXING BOWL JACKET AND VACUUM TO THE MIXING BOWL
7. CONTROL MIXING SPEED, TIME, TEMPERATURE AND VACUUM UNTIL DRYING IS COMPLETE
8. OPEN DISCHARGE VALVE TO DISCHARGE MIXTURE INTO AWAITING CONTAINERS
9. CLEAN MIXER BY FLUSHING WITH CLEANING SOLUTION

FIGURE 7: STEPS IN PREPARING A TYPICAL PYROMIXTURE

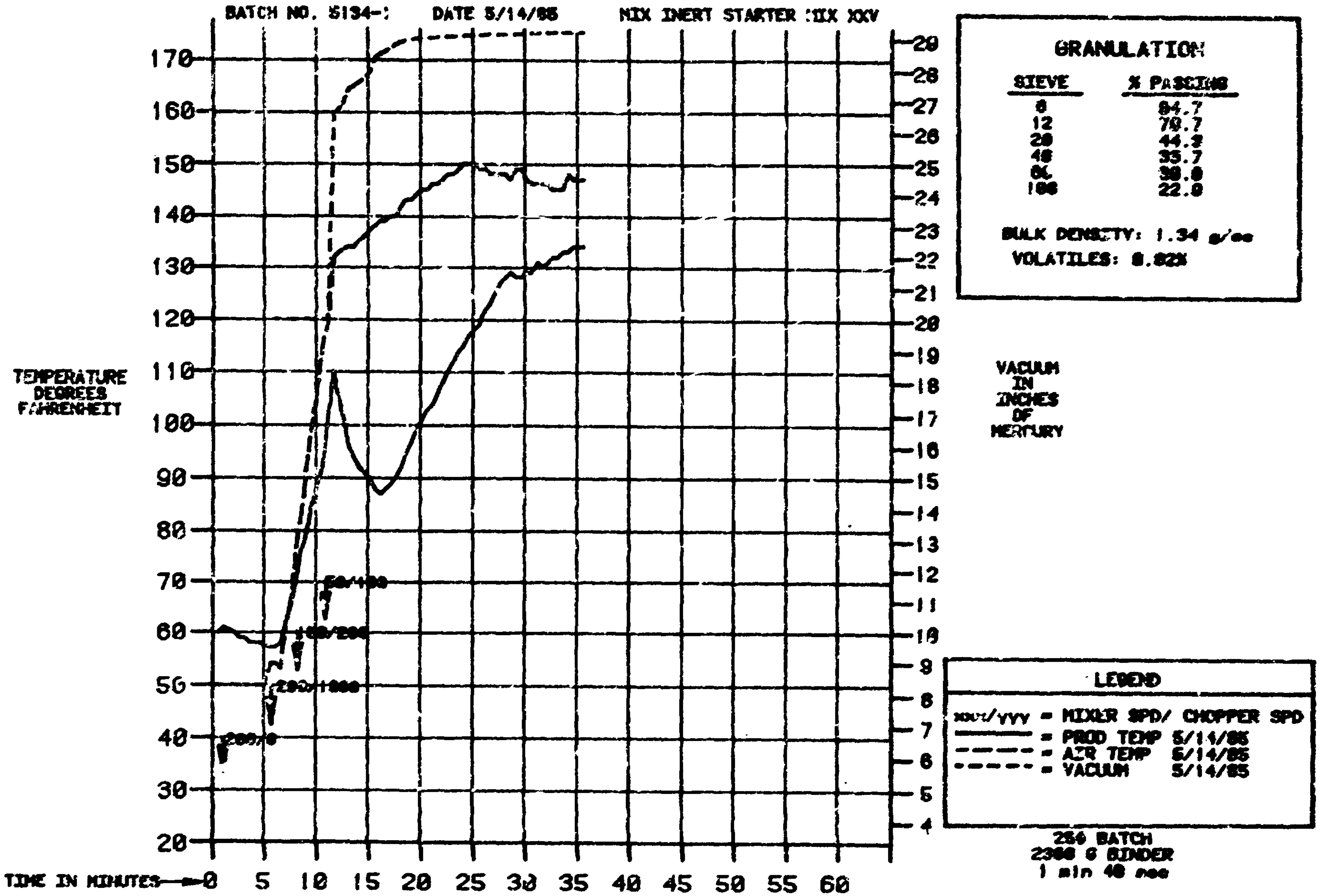

FIGURE 8: MIGRAD OPERATING PARAMETERS

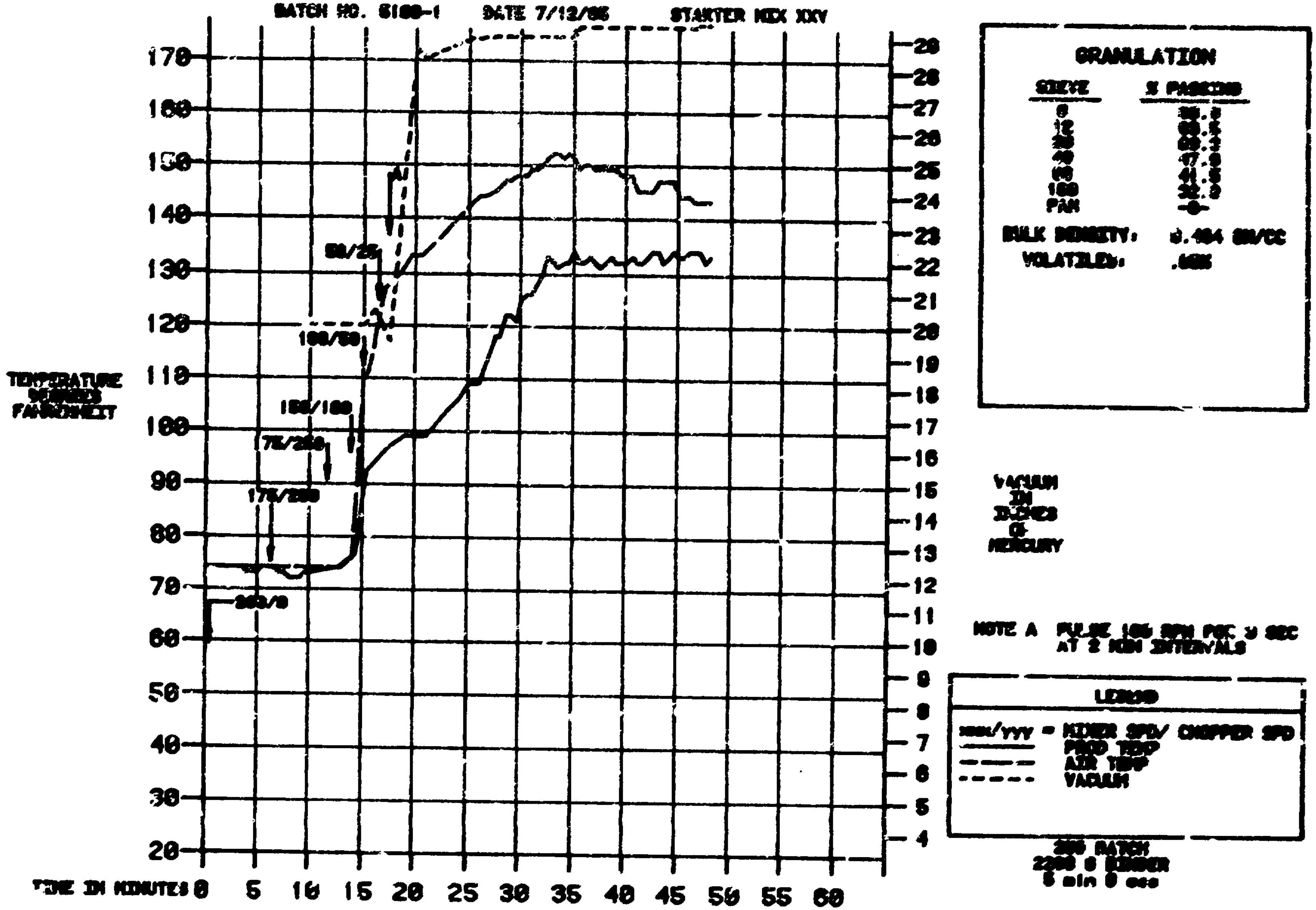

FIGURE 9: MIGRAD OPERATING PARAMETERS

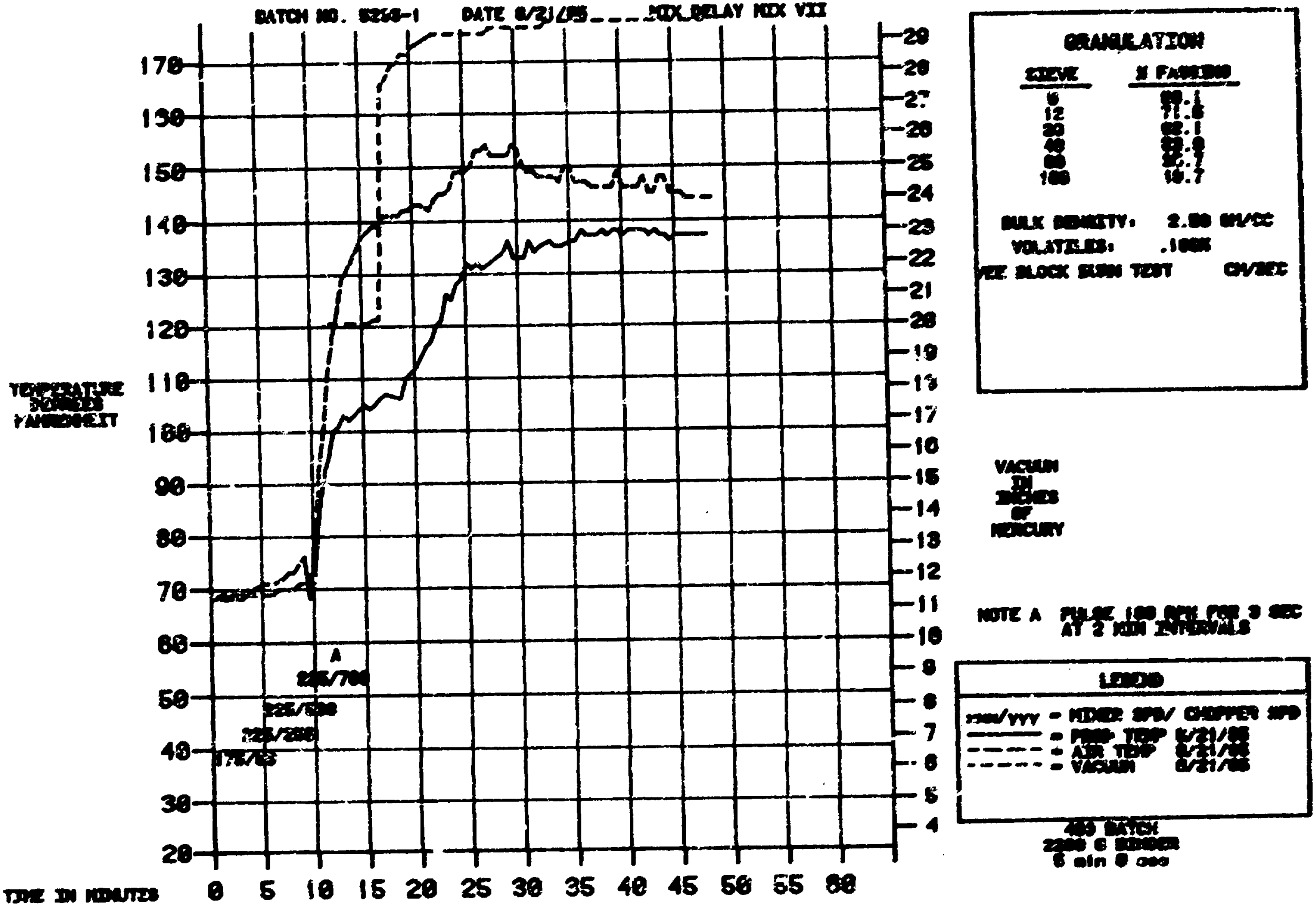

FIGURE 10: MIGRAD OPERATING PARAMETERS

HAZARDS CLASSIFICATION TESTS

- AUTOIGNITION TEMPERATURE
- DECOMPOSITION TEMPERATURE
- EXPLOSION TEMPERATURE
- BULK DENSITY
- GAS VOLUME
- HEAT OF COMBUSTION
- HEAT OF REACTION
- PROPAGATION INDEX
- THERMAL STABILITY
- WEIGHT LOSS
- CARD GAP TEST
- DETONATION TEST
- ELECTRICAL SPARK SENSITIVITY
- ROTARY FRICTION
- IGNITION & UNCONFINED BURNING
- BoE IMPACT SENSITIVITY
- BURN TIME (CUBE & VEE)
- PEAK PRESSURE
- PRESSURE VS TIME

FULL SCALE BLENDING TESTS

- MIXING TESTS USING FULL SCALE SIMULATOR
- "WORST CASE" INITIATION
- FIRE DETECTION/SUPPRESSION

FIGURE 11: SAFETY CERTIFICATION TESTS

TABLE 1

PYROMIXTURE SAFETY DATA

ITEM NUMBER	PYROMIXTURE IDENTIFICATION	INSTALLATION	AUTOIGNITION TEMP (°C)	DECOMPOSITION TEMP (°C)	EXPLOSION TEMP @ 5 sec. °C	BULK DENSITY (g/cc)	FUEL/OXIDIZER RATIO	GAS VOLUME (cc/g)	HEAT OF COMBUSTION (cal/g)	HEAT OF REACTION (cal/g)	PROPAGATION INDEX	THERMAL STABILITY (75°C)	CARD GAP TEST	DETONATION TEST	ELECTRICAL SPARK (Joules)	ROTO FRICTION "E"	ROTO FRICTION "e"	ROTO FRICTION "Es"	IGN. AND UNCONFINED BURN	ERL IMPACT (in.)	BURN TIME sec/cm CUBE σ	BURN TIME CUBE ST	BURN TIME "VEE" σ	BURN TIME "VEE" ST	PEAK PRESSURE (psi)	TIME TO PEAK (ms)	RATE OF RISE (psi/sec)
1	[illegible] TRACER [illegible]	LCAAP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	4.4	[illegible]	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	[illegible] TRACER [illegible]	LCAAP	[illegible]	[illegible]	231	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	14.2	[illegible]	[illegible]	N/A	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	ILLUMINANT MIX [illegible]	LHAAP	494	[illegible]	[illegible]	[illegible]	1.31	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	[illegible] FLARE MIX [illegible]	LHAAP	440	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.0	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17.0
5	[illegible] IGNITION MIX [illegible]	LHAAP	[illegible]	[illegible]	[illegible]	[illegible]	1.07	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	44.7	[illegible]	[illegible]	NE	[illegible]	[illegible]	1.77	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6	[illegible] TRACER [illegible]	LCAAP	[illegible]	[illegible]	[illegible]	1.17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7	[illegible] IGNITION MIX [illegible]	LCAAP	[illegible]	277	[illegible]	1.07	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8	[illegible] INCENDIARY MIX [illegible]	LCAAP	[illegible]	477	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	8.7	12.4	[illegible]	N/A	[illegible]	N/A	N/A	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9	I-136 IGNITION MIX [illegible]	LCAAP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	NE	[illegible]	[illegible]	1.77	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	[illegible] TRACER [illegible]	LSAAP	344	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
11	I-137 PELLET MIX [illegible]	LSAAP	372	410	447	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	1.0	[illegible]	[illegible]	[illegible]	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
12	[illegible] DELAY MIX [illegible]	LSAAP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
13	[illegible] DELAY [illegible] MIX [illegible]	LSAAP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	N/A	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
14	[illegible] ILLUM MIX [illegible]	CAAA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	14.4	6.0	[illegible]	N/A	[illegible]	N/A	N/A	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
15	[illegible]-117 FIRST FIRE MIL-[illegible]	CAAA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	N/A	[illegible]	N/A	N/A	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
16	DELAY MIX VII [illegible]	PBA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
17	FIRST FIRE MIX [illegible]	PBA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
18	FIRST FIRE VI [illegible]	PBA	777	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
19	40mm IGNITION MIX [illegible]	PBA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20	STARTER MIX XIV [illegible]	PBA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
21	[illegible] MIX VI [illegible]	PBA	170	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	3.7	[illegible]	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
22	[illegible] SMOKE [illegible]	CAAA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	*	[illegible]	*	0	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	N/A	[illegible]	N/A	N/A	*	*	*	*	*
23	[illegible] IGNITION MIX [illegible]	CAAA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	N/A	[illegible]	N/A	N/A	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
24	[illegible] FLASH MIX [illegible]	LAAP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	ND	NE	[illegible]	[illegible]	[illegible]	[illegible]	NE	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

NOTES: *=SAMPLE FAILED TO IGNITE OR SUSTAIN BURNING. ND=NO DETONATION. NE=NO EXPLOSION. 0=GOOD. N/A=NO TEST RESULTS

TABLE 2
KEY SAFETY DATA

NOMENCLATURE	1	2	3	4	5
DELAY MIXTURE VII	0.12	>50	10	214	40.5
FIRST FIRE VI	0.11	$\boxed{0.28}$	10	4185	38
FIRST FIRE VII	0.20	>50	10	1329	66.8
40mm IGNITION MIXTURE	$\boxed{0.05}$	$\boxed{0.107}$	$\boxed{3.75}$	$\boxed{86}$	$\boxed{265.8}$
STARTER MIXTURE XXV	0.20	>50	$\boxed{3.75}$	2145	$\boxed{261.4}$
FUEL MIXTURE VI	$\boxed{0.01}$	$\boxed{0.002}$	10	$\boxed{56}$	$\boxed{490}$
SW522 SMOKE MIXTURE	N/A	>50	$\boxed{3.75}$	$\boxed{52}$	?
MK38 IGNITION MIXTURE	0.20	>50	10	2231	157.6
M117/118 YELLOW 1ST FIRE MIX	0.29	>50	$\boxed{3.75}$	3151	166.4
MK18-0 ILLUMINANT MIXTURE	0.26	>50	$\boxed{3.75}$	$\boxed{97}$	77.6
IGNITION MIXTURE #9235983	$\boxed{0.03}$	$\boxed{0.01}$	10	4322	82.7
M53 DELAY PREMIX	$\boxed{0.03}$	>50	$\boxed{3.75}$	1753	728
M13 TRACER MIXTURE(R508)	0.17	>50	$\boxed{3.75}$	$\boxed{53}$	268
PELLET MIXTURE #657421	$\boxed{0.04}$	12.5	$\boxed{3.75}$	47952	$\boxed{882}$
I-136 IGNITION MIXTURE	0.73	>50	10	588	25.5
I-548 IGNITION MIXTURE	1.81	>50	$\boxed{3.75}$	$\boxed{66}$	38.2
IM-28 INCENDIARY MIXTURE	$\boxed{0.01}$	>50	$\boxed{3.75}$	$\boxed{19}$	$\boxed{303.6}$
R256 TRACER MIXTURE	0.87	>50	10	$\boxed{45}$	42.3
R284 TRACER MIXTURE	1.14	>50	10	$\boxed{68}$	83.4
R505 TRACER MIXTURE	1.85	>50	10	235	47.9
M22 FLASH MIXTURE	$\boxed{0.01}$	>50	$\boxed{3.75}$	>55041	$\boxed{2123}$
ILLUMINANT MIXTURE #8888446	3.11	>50	10	204	19.8
M49A1 TRIP FLARE MIXTURE	2.67	>50	10	197	17
IGNITION MIXTURE(M49A1)	0.85	>50	10	158	15.2

1=VEE-BURN TEST (SEC/CM) ALWAYS AT APPARENT BULK DENSITY
2=ELECTRO-SPARK SENSITIVITY (JOULES)
3=BoE IMPACT SENSITIVITY (INCHES)
4="Eq" ROTO-FRICTION VALUE (FT-LB ^{2}/SEC) (THE LOWER THE VALUE
THE MORE SENSITIVE THE MATERIAL)
5=PRESSURE RATES OF RISE (PSI/SEC)
⬭ EXCEEDS THRESHOLD LEVEL

DELAY MIXTURE VII DWG. NO. C143-12-5

INGREDIENTS	MATERIAL SPECIFICATION	PERCENTAGE
Silicon	MIL-S-230	15.00
Red Lead	TT-R-191	85.00
Binder*	0-A-51/MIL-N-244	1.80

*Nitrocellulose/Acetone 8/92% added by dry weight.

FIRST FIRE VI MIXTURE DWG. NO. B143-9-2

Silicon	MIL-S-230	33.00
Red Lead	TT-R-191	55.00
Titanium	--	12.00
Binder*	0-A-51/MIL-N-244	1.80

*Nitrocelloluse/Acetone 8/92% added by dry weight.

FIRST FIRE MIXTURE VII DWG. NO. B143-9-1

Silicon	MIL-S-230	25.00
Red Lead	TT-R-191	25.00
Titanium	MIL-T-13405	25.00
Iron Oxide (Red)	TT-N-244	25.00
Binder*	0-A-51/MIL-N-244	3.00

*Nitrocelloluse/Acetone 8/92% added by dry weight.

40-mm IGNITION MIXTURE DWG. NO. 9322380

Potassium Nitrate	MIL-P-156	10.00
Boron	MIL-B-51092	21.00
Barium Chromate	MIL-B-550	65.00
VAAR*	MIL-V-50433	4.00

*Acetone can be added in sufficient amounts for proper consistency.

STARTER MIXTURE XXV DWG. NO. B13-19-96

Silicon	MIL-S-230	26.00
Potassium Nitrate	MIL-P-156	35.00
Charcoal	JAN-C-178	4.00
Iron Oxide (Black)	MIL-I-275	22.00
Aluminum	MIL-A-512	13.00
Binder*	0-A-51/MIL-N-244	3.00

*Nitrocellulose/Acetone 8/92% added by dry weight.

FUEL MIXTURE VI DWG. NO. B143-10-1

Potassium Clorate	MIL-P-150	42.00
Sugar	JJJ-S-791	28.00
Magnesium Carbonate	MIL-M-11361B	30.00
Binder*	0-A-51/MIL-N-244	3.40

*Nitrocellulose/Acetone 8/92% added by dry weight.

Figure 12: Pyrotechnic Formulations

SW522 SMOKE MIXTURE DWG. NO. 19200-9333792

Zinc Dust	MIL-Z-365A	40.00
Potassium Perchlorate	MIL-P-217, GR A, CL A	20.00
Potassium Nitrate	MIL-P-156, CL 2	20.00
Aluminum	MIL-P-14067, Type II	20.00

MK-38 IGNITION MIXTURE DWG. NO. 10001-2113767

Aluminum	MIL-P-14067, Type II	15.00
Boron	MIL-B-51092	5.10
Potassium Nitrate	MIL-P-156, CL 2	35.00
Acetone	0-A-51	10.60
Hexane	WS-7692	31.80
Binder*	DWG 2151330	2.00

*Copolymer cut into smaller pieces.

MK-117 FIRST FIRE MIXTURE DWG. NO. MIL-STD-720A

Barium Nitrate	MIL-B-162	50.00
Tetranitrocarbazole	MIL-T-13723	10.00
Zirconium Hydride	MIL-Z-21353	15.00
Silicon	MIL-S-230, GR B, CL B	20.00
Catalyst (Lupersol DDM)	MIL-STD-708	
Resin (Laminac 4110)	MIL-STD-708	5.00

M18-0 ILLUMINATING MIXTURE DWG. NO. 10001-2151714

Magnesium	MIL-P-14067	60.00
Sodium Nitrate	MIL-S-322, GR B, CL 2	35.00
Flare Binder System*		5.00

*Epoxy resin 70% Dow Chem Co-DER-321 CIBA Prod. Co-ARAlidite 507 Polymide Curring Agent Dow Chem DEH-14 Gen. Mill-Versamid 140

M549 DELAY IGNITION MIXTURE DWG. NO. 9235983

Zirconium	MIL-Z-390	65.00
Iron Oxide	MIL-I-706	25.00
Diatomaceous Earth		10.00
VAAR	MIL-V-50433	1.00

M53 DELAY MIXTURE DWG. NO. 9231376

Silicon	MIL-S-230	18.35
Red Lead Oxide	TT-R-191	73.31
Binder*		8.34

*Binder: Nitrocelloluse 98%, Ethyl-Centralite 2%, Acetone.

M13 (R508 TRACER) MIXTURE DWG. NO. 11738312 HCSDS NO. 321 Rev

Strontium Nitrate	MIL-S-20322	44.00
Magnesium (100/200)	MIL-P-13067	21.00
Magnesium (200/325)	MIL-P-14067	21.00
Dechlorane	DWG. NO. 11738314	7.00
VAAR	MIL-V-50433	7.00

Figure 12: Pyrotechnic Formulations (Continued)

PELLET MIXTURE I-136 DWG. NO. 657421

Potassium Nitrate	MIL-P-156	70.70
Boron (Amorphous)	0S1168	23.70
Binder*		5.60

*Laminac Resin 98%; Lupersol DDM 2%, Acetone.

I-136 IGNITION MIXTURE DWG. NO. B10522417 HCSDS NO. 1314 Rev

Calcium Resinate	MIL-C-20470	10.00
Strontium Peroxide	MIL-S-612	90.00

I548 IGNITION MIXTURE DWG. NO. B11075772 HCSDS NO. 1313 Rev

Strontium Peroxide	MIL-S-612	65.00
Calcium Resinate	MIL-C-20470, Type I	13.00
Calcium Resinate	MIL-C-20470, Type II	7.00
Magnesium	MIL-M-382, Type III, Gran II	15.00

IM-28 INCENDIARY MIXTURE DWG. NO. B10522394

Barium Nitrate	MIL-B-162	40.00
Potassium Perchlorate	MIL-P-217	20.00
Mag-Aluminum Alloy	JAN-M-454	50.00

R256 TRACER MIXTURE DWG. NO. B10521775 HCSDS NO. 1356 Rev

Strontium Peroxide	MIL-S-612	26.70
Strontium Oxalate	MIL-S-12210	5.00
Calcium Resinate	MIL-C-20470, Type I	6.70
Calcium Resinate	MIL-C-20470, Type II	1.60
Strontium Nitrate	MIL-S-20322	33.30
Magnesium	MIL-M-382, Type III, Gran II	26.70

R284 TRACER MIXTURE DWG. NO. B10522416 HCSDS NO. 10207 Rev B

Strontium Nitrate	MIL-S-20322	55.00
Magnesium	MIL-M-382, Type III, Gran II	28.00
Polyvinyl Chloride	MIL-P-20307	17.00

R505 TRACER MIXTURE DWG. NO. C11075777 HCSDS NO. 1345 Rev

Strontium Nitrate	MIL-S-20333, GR A or B	42.00 (Min)
Calcium Resinate	MIL-C-20470, Type II	20.25 (Max)
Magnesium	MIL-M-382, Type III, Gran II	25.00
Oxamide	MIL-O-60863, GR B, Note 4	13.12 (Max)
Polyethylene	L-P390, Type I, GR 2	3.75 (Max)

M22 FLASH MIXTURE DWG. NO. 11749643

Magnesium (200/325)	MIL-P-14067, Type I	75.00
Polytetraflourethylene	L-P-403, Type IV, Class 1	10.00
Flouroelastomer	117949634	15.00

Figure 12: Pyrotechnic Formulations (Continued)

ILLUMINANT MIXTURE DWG. NO. 8886446 HCSDS NO. 977 Rev C

Magnesium (30/50)	MIL-P-14067	51.00
Sodium Nitrate	DWG. NO. 9216973 (prilled)	42.00
Binder*		7.00

*Epon 828 25.5%, Polysulfide LP-33 71.4%, Hardener DEH 24 3.1%

M49A1 TRIP FLARE MIXTURE DWG. NO. 9269024 HCSDS NO. 1081 Rev

Magnesium (20/50)	MIL-P-14067	40.00
Sodium Nitrate	MIL-S-322	49.00
Binder*		11.00

*Laminac 4116 98.6%, Lupersol DDM 1.3%, Cobalt Naphenate 0.01%

M49A1 IGNITION MIXTURE DWG. NO. 9269025 HCSDS NO. 347 Rev D

Sodium Nitrate	MIL-S-322	45.90
Magnesium (30/50)	MIL-P-14067, Type IV	49.40
VAAR	MIL-V-50433	4.70

Figure 12: Pyrotechnic Formulations (Continued)

VENTED SUPPRESSIVE SHIELDING IN PYROTECHNIC OPERATIONS

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SYNOPSIS

Technological advances in propulsion system design and corresponding demands for more energetic igniter materials have pressed the capacity of rocket igniter manufacturing facilities at the Naval Ordnance Station, Indian Head. A survey of operations was made and methods of enhancing space utilization and safety were evaluated. The vented suppressive shielding technology was selected. Application of this technology permits handling of increased pyrotechnic quantity and reduces non-productive personnel movement with improved safety. Design considerations and testing results are presented. (The complete engineering analysis and test results are to be published as a NAVORDSTA, Indian Head technical report.)

I. INTRODUCTION

Manufacturing requirements for rocket igniters were exceeding the capacity of existing facilities of the Ignition Devices Branch, Manufacturing Technology Division at the Naval Ordnance Station, Indian Head. Enhanced productivity was required without compromising safety. This problem was approached and resolved by the following actions.

First, manufacturing operations were surveyed to identify hazards and to analyze operation functions, material flow and process stations, equipment, and igniter compositions used.

The survey was followed by the decision to use vented suppressive shielding to improve utilization of space and safety. Vented Suppressive Shielding (VSS) is a form of barricade developed to protect personnel and equipment from the effect of accidental explosions.

The decision was implemented by contracting with T & E International of Bel Air Maryland to design, fabricate and test several VSS. These have been installed at NOS Indian Head. This paper reports results of the survey, describes the VSS designs, presents the test results and explains briefly the NOS implementation in the rocket igniter manufacturing area.

II. SURVEY OF OPERATIONS

Rocket igniter manufacturing operations were surveyed. The objective of the survey was to gather the data necessary for space utilization improvements in the following categories: physical measurements, operations and functions, work stations, material flow, equipment and facilities. Floor plans and buildings were reviewed to determine type of structure, dimensions and services available.

a. Operations

Typical igniter manufacturing operations were investigated and analyzed in the survey. Standard Job Procedures (SJP's) were studied and classified according to the type of Operation. Several of these (SJP's) were analyzed to develop general categories of manufacturing functions. From this analysis, seven classes of manufacturing functions were obtained and every (SJP) was then reviewed to prepare a manufacturing function matrix for the 18 items currently manufactured in the facility. The seven classes of manufacturing functions identified were:

Setup of equipment

Preparation of material and parts

Loading of pyrotechnic material

Assembly

Packout

Disassembly for rework

Repair

b. Material Flow

The objective of the material flow system is to have the work flow safely and smoothly from one station to another through the facility with a minimum of wasted space and effort. Work in the rocket igniter facility is primarily product oriented, although certain specific operations, such as soldering, painting, gluing and welding must be fixed in place for health and safety reasons or because the process equipment is not easily moved.

When process equipment and in-process storage is placed in a layout, its location is usually optimized to minimize material handling and space demands. However, the optimum operation layout is not the same for all igniters and is not always practical because of constraints for safe operation and storage of hazardous material. Because of the variety of products manufactured and the limited quantities produced, facilities had to be flexible and dedicated manufacturing lines were not feasible.

Analysis of the survey information resulted in several recommendations to improve space utilization and operational efficiency. These recommendations were to use VSS for the following:

1. Shielding barricade
2. Mobile vented shielding storage cart
3. Vented shielding test chamber

T & E International, Inc., accomplished this survey and was further contracted to design, fabricate and proof test the VSS equipment required.

iii. VENTED SUPPRESSIVE SHIELDING

VSS was developed as a part of the U. S. Army Manufacturing Technology Program to protect personnel and equipment from explosive incidents. The development of VSS has been reported in prior publications such as DOD Explosive Seminar minutes.

The VSS concept essentially was interlocked angle iron for fragment shielding and perforated steel plates and copper screen for heat absorption as shown in Figure 1. This combination allows explosion gas pressure to be vented at a controlled rate and cooled to limit thermal hazard.

The five suppressive shield group designs approved by the Department of Defense Explosives Safety Board (Groups 3, 4, 5, 6 and 81-mm) have been designed to meet requirements for most applications of ammunition load, assemble, and pack (LAP). However, specific shield requirements will vary with other applications and, even with LAP applications, design details will vary from plant to plant and between munitions or different operations on the line. It is necessary to modify the approved shields to adapt them to the operation under consideration. A modified group 5 design was applied to the NOS, Indian Head rocket igniter manufacturing operations.

Evaluation tests were conducted in a test fixture, shown in Figure 2. This fixture allowed for variation in shielding to evaluate different structural materials and arrangements.

IV. DESIGN OF VSS EQUIPMENT

Three items of equipment were designed. These were an igniter continuity test chamber, a mobile storage cart and a shielding wall for an igniter soldering facility.

a. Continuity Test Chamber

The continuity test chamber designed by T & EI is vented on three sides with solid steel plates on top, bottom, and door. Hot gaseous products of combustion are vented through the three VSS side panels and directed away from the operator station in front of the solid steel door. The VSS chamber vents the products of combustion, reduces their pressure and temperature, confines hot particles and metal fragments, and permits water from the deluge system to enter. The test chamber is shown in Figure 3.

b. Mobile VSS Storage Cart

The mobile wheeled storage cart was designed with drawers using the vented shield concept. This cart is shown in Figure 4. The cart was designed so it can be wheeled in position convenient to the manufacturing operations and can permit the operators to move quantities of completed and in-process items to other operations and/or holding bays. The operational concept includes a cart with in-process igniters in the drawers at a work station and the completed devices in the drawers of another cart. An in-process igniter component is removed from the drawer by an operator, the operation is performed and the completed device is placed in the drawer of another cart. When the drawers in a cart are filled with completed work, the cart with in-process igniter components is empty and is taken to be refilled. The cart filled with completed igniter devices is wheeled to a staging or storage area for packaging and shipment. Use of the VSS cart minimizes the handling of components and completed igniters and allows increased quantity of material at a work station without increasing risk. The cart is shown in Figure 4.

c. Labyrinth VSS Wall

A VSS labyrinth wall was designed for an igniter induction soldering operation. This shield allows the operator to remain in the same bay during the soldering operation and improves space utilization. This shielding installation is shown in Figure 5 The wall was designed to the standards for Type 5 shielding approved by the DDESB, consequently, no proof tests were required for the labyrinth shield.

V. TESTING PLAN

The engineering design and proof tests had the following three major purposes:

a. Demonstrate empirically that the suppressive shield panels reduce the hazardous effects of fragments, hot particles, flame, heat flux, and gas pressure to an operator safe level.

b. Determine by test the maximum temperature, force, hot particle impact, and fragment impact which a given VSS panel will withstand.

c. Obtain and record data for suppression and containment of the hazardous flame, metal fragments, hot particles, and pressure effects from combustion of up to 2250 grams of igniter material such as, MTV or BKNO3 within the continuity test equipment. The purpose of this date, obtained from igniter quantities which are 25 percent above the design charge is to justify safety for use with 1800 grams.

A test fixture was fabricated to permit empirical evaluation of design variables. Proof tests were performed on the test chamber and the portable storage cart. Instrumentation for blast pressure, temperature, strain and heat flux was provided for the testing. Photo and video documentation was obtained on the tests. The testing was conducted for T & E International by the Wright-Malta Test Facility in New York.

VI. TEST RESULTS

A total of 18 tests were conducted in the test program for the test fixture and continuity test chamber. The first nine exploratory, open air tests established the ignition method and provided a photographic and video base for visual comparison of suppression effects. Seven special panel tests provided data for determination of vented suppressive shield cart (VSSC) panel component material, panel structure, and a maximum igniter charge weight that would not plastically deform the panel components. Two proof tests verified the VSS equipment was adequate for use with igniters with one pound of BKNO_3 or MTV material.

The evaluation tests are shown in Table 1. Summary of Tests. High speed motion picture and video-tapes provide a comparison of unsuppressed (open air) and suppressed (in the vented shielding) burning of the test materials. Data from the pressure, heat flux and thermal instrumentation have been studied by T & EI and significant features are reported.

Design engineering analysis indicated that the maximum pressure expected within the vented suppressive shield equipment (VSSE) would be 72 psi and pressure within the vented suppressive shield test fixture (VSSF) would be 170 psi with an igniter charge of 100 grams of BKNO3. This analysis assumed that the igniter material burned before any gas vented through the panels. However, from the tests, it is clear that the products of combustion were venting through the panels as the BKNO3 is burning. For charge weights up to 454 grams BKNO3, no measurable pressure builds up in either the VSSF or the VSSE (continuity test chamber). Consequently, no measurable blast pressure is produced outside of either the VSSF or VSSE.

Testing with MTV reveals that it is harder to ignite and, at atmospheric pressure, is slower to burn than BKNO3; therefore, internal gas pressures with MTV also did not build up to a measurable level.

Noise and smoke from audio and visual observation demonstrate turbulent gas flow as the MTV products of combustion are forced through the VSS panels with a pop and a hissing sound. A remarkable result of burning MTV is combustible products of combustion. These do not oxidize completely in the oxygen deficient atmosphere within the test fixture of VSSE, but are forced through the VSS panels and ignite in the ambient air. This phenomena is seen in the tapes and high speed films of the tests, and was clearly evident in observation of the test. Study of the chemical reactions which occur in burning MTV indicate intermediate products which are toxic as well as combustible. It is possible to reduce the heat content of the vented gases by redesign of the panels, and it may be possible to reduce the heat to such a degree that the intermediate products of combustion will not burn.

Data on fragments, particles, and smoke were obtained from high speed motion pictures, video tapes, and observation of the test. Since the first nine open air tests were conducted with the charge in paper cups, fragments other than the electric match remnants were not expected, but smoke and flying burning grains and pellets were expected and were seen. Many burning MTV grains were thrown more than 10 feet from the ignition point and, in the high speed motion pictures, burning BKNO3 pellets were seen flying several feet from the ignition point.

Every test released quantities of smoke. A short, brilliant flash and quickly dissipating white smoke accompanied burning BKNO3, but thick black billows of smoke and flame from burning MTV lasted about 5 seconds. Heat flux from tests in the VSSF are listed in Table II.

Heat flux and temperature data for Test 10 indicate values well below threshold for injury when 125 grams of BKNO3 are ignited and burned in the VSSF with panels which consist of six aluminum perforated plates, five copper wire cloth sheets and no angle units. However, the thermal effects data from Test 11 indicates marginal protection for personnel when 125 grams of MTV are ignited and burned in the VSSF with the aluminum perforated plates, copper wire cloth, and no angle units. Subsequent to Test 11, the level of suppression of the VSSF was increased by substituting an angle unit for two of the corrugated perforated plates and, to combat the melting, steel components were substituted for aluminum. The angle units used were fabricated from 1/2 inch angles. Thermal data from Test 14 with MTV show the heat flux and temperatures are reduced below the maximum allowable level as expected with the increased suppression.

After the tests at the 125 gram proof charge level demonstrated successful suppression of thermal hazards, the test plan was followed to increase igniter charge weights and explore the limits of protection and strength of the panel layers in the VSSF. Accordingly, igniter charge weights were increased stepwise to 454 grams, at which point protection limits began to appear. Table III lists tests with 454 grams of igniter material and shows heat flux at the allowable limit when BKNO3 is burned in the VSSF configured with four perforated steel plates, five copper wire cloth sheets, and an angle unit with 1/2 inch steel angles. The data also show the expected increase in thermal suppression when the internal volume is increased from 1 cu. ft. in the VSSF to 3.4 cu. ft. in the VSS continuity test chamber.

Since the data on thermal effects showed the allowable limit had been reached and burning time data from the light sensor inside the VSSF showed decreased burning time which indicates the onset of pressure confinement effects, the test were concluded at the 454 gram level.

VII. MOBILE VSS CART TEST RESULTS

A total of 6 tests listed in Table IV were conducted to evaluate the mobile VSSC. Three open air tests were conducted to provide a photographic and video base for visual comparison of suppression effects between the open air and in-cart tests. Three in-cart proof tests were conducted to evaluate the design and fabrication techniques of the cart. These proof tests verified the adequacy of the cart for use with 16 MK287 MOD-0 igniters and with open pan quantities of BKNO3 and MTV up to 5 lbs. Heat flux tests from the cart tests are presented in Table V.

The criteria necessary to design an operational shield which will protect personnel from thermal, pressure, and fragment hazards resulting from detonation of explosives or deflagration of propellants and igniter compositions are given in DOD MIL STD - 398, "Shields, Operational for Ammunition Operations, Criteria for Design of and Test for Acceptance," dated 5 Nov. 76. Allowable heat flux is determined by:

$$f = 0.062/t^{0.7423}$$

f = heat flux in cal./cm^2 - sec

t = total time in seconds that a person is exposed to the radiant heat

Thermal effects constraints require that: (a) all operating personnel be located at a distance from the shield that assures their exposure is less than the flux determined by the above equation, and (b) the upper torso of an operator's body shall not be subjected to any visible fire or flame. Flame impingement upon the lower portion of the body may be permitted provided that the heat flux specified above is not exceeded.

Video tapes and high speed motion picture photographs of the VSSC indicate no visible flame at the operator's position in front of the drawers. Visible flame extended less than 3 feet to the side of the cart and 4 feet above. Measured duration of heat flux was in every case less than 1.25 seconds. From the equation above allowable heat flux would be 0.53 cal./cm2 - sec. The measured values of heat flux at the operator's station, which is 30 inches from the VSSC in front of the drawers are below that limit. Consequently, visible flame, not heat flux, is the determining factor for personnel safety. Operators in front of the drawers would not be subjected to visible flame. Casual visitors who pass by within 1 foot of the VSSC side panels during burning would be exposed to heat flux above the threshold for burns on exposed skin. At 5 feet from the side panels, the heat flux is below the threshold.

VIII. CONCLUSIONS

Analysis of the test results for thermal and pressure exposure proves that the VSS continuity test chamber and the Mobile VSS Storage Cart will suppress the hazardous effects resulting from unintentional ignition of pyrotechnic material and devices during manufacturing operations up to the design quantity. Modifications to the cart design are being considered to reduce weight and possibly increase suppressive capability.

The VSS continuity test chamber and Mobile VSS Storage Cart are being incorporated into igniter manufacturing operations. A labyrinth VSS wall has been installed to allow rocket igniter assembly and induction soldering in one bay for productivity enhancement. The operation arrangement is indicated in Figure 6.

TABLE 1. SUMMARY OF VSS TESTS

Test No.	Material	Quantity	Fixture	Remarks
1	BKNO3	50 gms.	Open Air	For fireball evaluation
2	BKNO3	100 gms.	Open Air	For fireball evaluation
3	BKNO3	125 gms.	Open Air	For fireball evaluation
4	MTV	50 gms.	Open Air	No test, did not ignite*
5	MTV	50 gms.	Open Air	No test, did not ignite*
6	MTV	50 gms.	Open Air	For fireball evaluation
7	MTV	100 gms.	Open Air	No test, did not ignite*
8	MTV	100 gms.	Open Air	For fireball evaluation
9	MTV	125 gms.	Open Air	For fireball evaluation
10	BKNO3	125 gms.	Test fixture	Smoke, no damage aluminum panels
11	MTV	125 gms.	No angles	Melted inner aluminum perforated plate.
-	BKNO3	125 gms.	Open Air	Demonstrations for NOSIH personnel
-	MTV	125 gms.	Open Air	Demonstrations for NOSIH personnel
12	BKNO3	250 gms.	Test fixture steel panels	Smoke & flash no damage
13	BKNO3	454 gms.	Test fixture steel panels	Smoke & flash no damage
14	MTV	125 gms.	Test fixture steel panels	Smoke & flash, no damage
15	MTV	250 gms.	Test fixture steel panels	Smoke & flash, no damage

*Difficulty was experienced in developing a reliable method for igniting the MTV.

TABLE II. HEAT FLUX FROM TEST FIXTURE (VSSF)

Test No.	Material	Quantity	Gage Location	Heat Flux Cal/cm 2-sec	Remarks
10	BKNO3	125 gms	1.0 ft. 2.5 5.0	0.331 0.056 0.002	Six aluminum perforated plates, no angle units
11	MTV	125 gms	1.0 2.5 5.0	Off scale 0.023 0.026	Six aluminum perforated plates, no angle units
14	MTV	125 gms	1.0 2.5 2.0	0.030 0.013 0.003	Four steel perforated plates, 1/2 inch steel angle unit

TABLE III. HEAT FLUX - PROOF TEST RESULTS

Test No.	Material	Quantity	Gage Location	Heat Flux Cal/cm 2-sec	Remarks
13	BKNO3	454 gms	1.0 ft. 2.5 5.0	1.9 2.3 0.5	Test fixture with 4 steel perforated plates and 1/2 inch angle unit
16	MTV	454 gms	1.0 2.5 5.0	0.6 0.4 0.1	Test fixture with 4 steel perforated plates and 1/2 inch angle unit
17	BKNO3	454 gms	1.0 2.5 5.0	0.3 0.6 0.1	Igniter electrical test chamber proof test
18	MTV	454 gms	1.0 2.5 5.0	0.3 0.1 0.1	Igniter electrical chamber proof test

TABLE IV. SUMMARY OF VSS CART TESTS

Test No.	Test Item	Quantity	Test Condition	Remarks
1	Bulk BKNO3	5 lbs	Open air	Material in metal can, open at top
2	Bulk MTV	5 lbs	Open air	Material in metal can, open at top
3	Igniter	1	Open air	One MK 287 MOD-0 for unsuppressed effect
4	Igniters	16	In cart	9 MK 287 MOD-0 igniters in second drawer. Seven MK 287 MODO igniters in top drawer
5	BKNO3	5 lbs	In cart	9 pans in one drawer and 9 pans in next drawer above
6	MTV in	5 lbs	In cart	9 pans in one drawer and 9

VENTED SUPPRESIVE SHIELDING

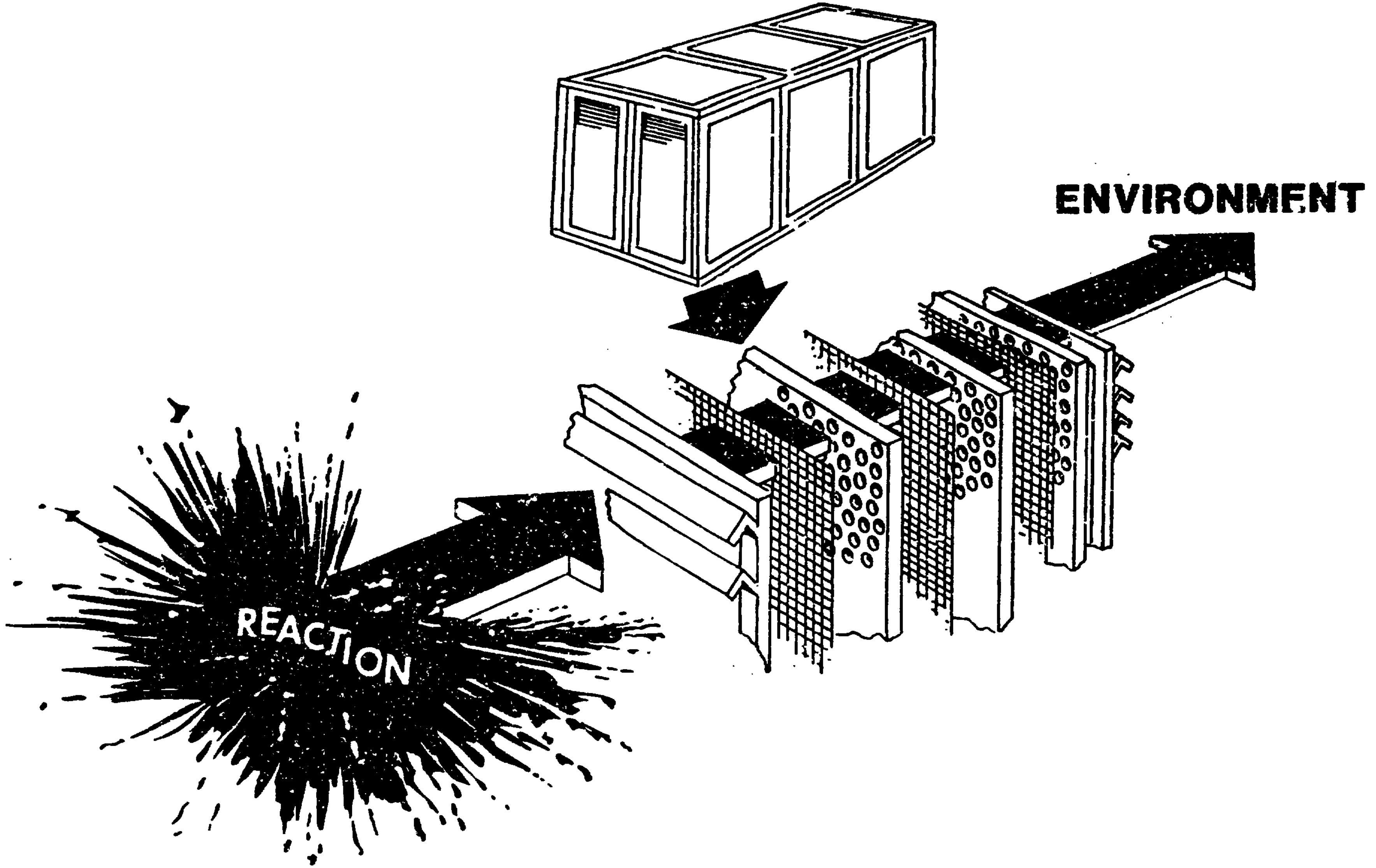


FIGURE 1.

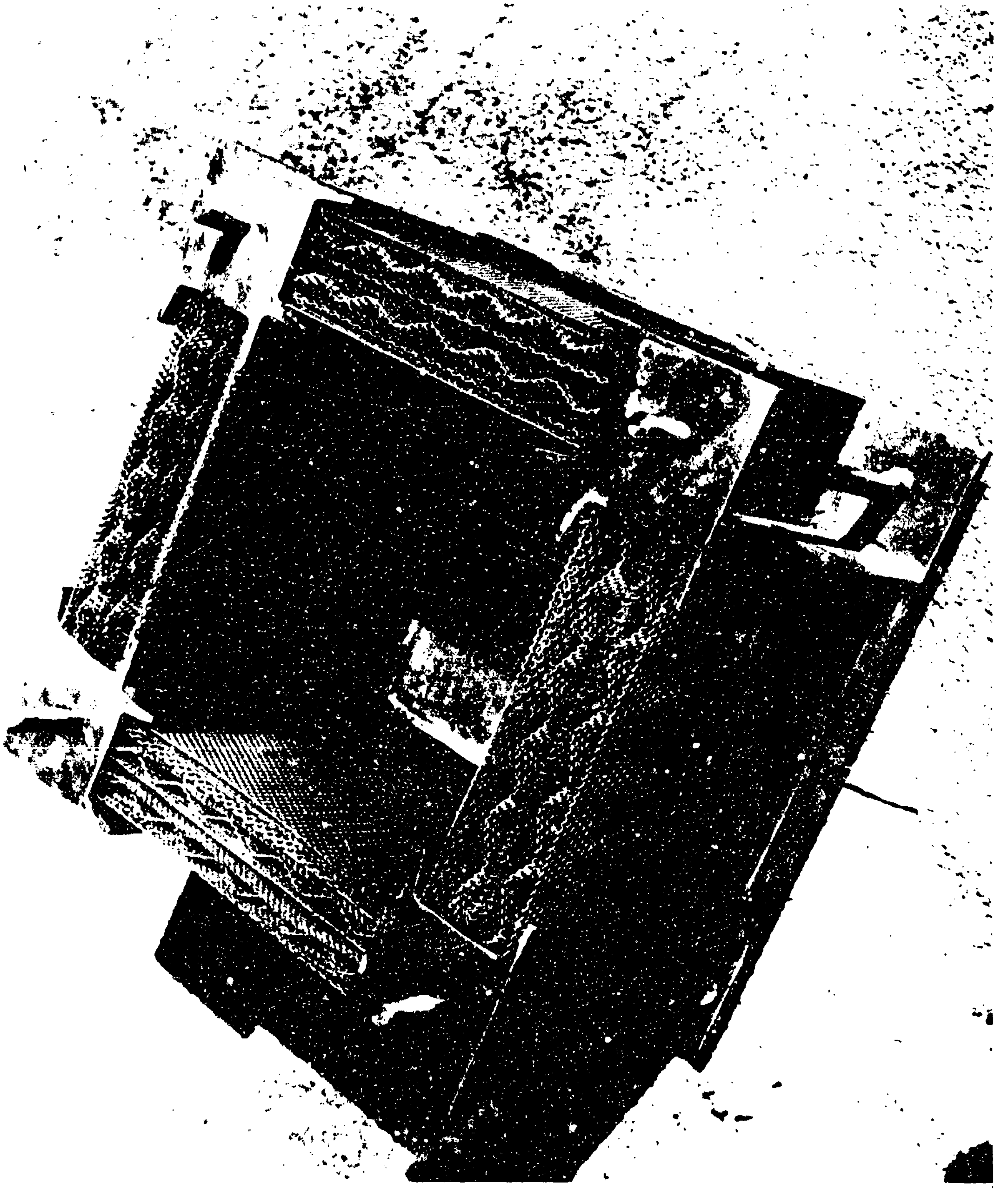


FIGURE 2. TEST FIXTURE

FIGURE 3. CONTINUITY TEST CHAMBER

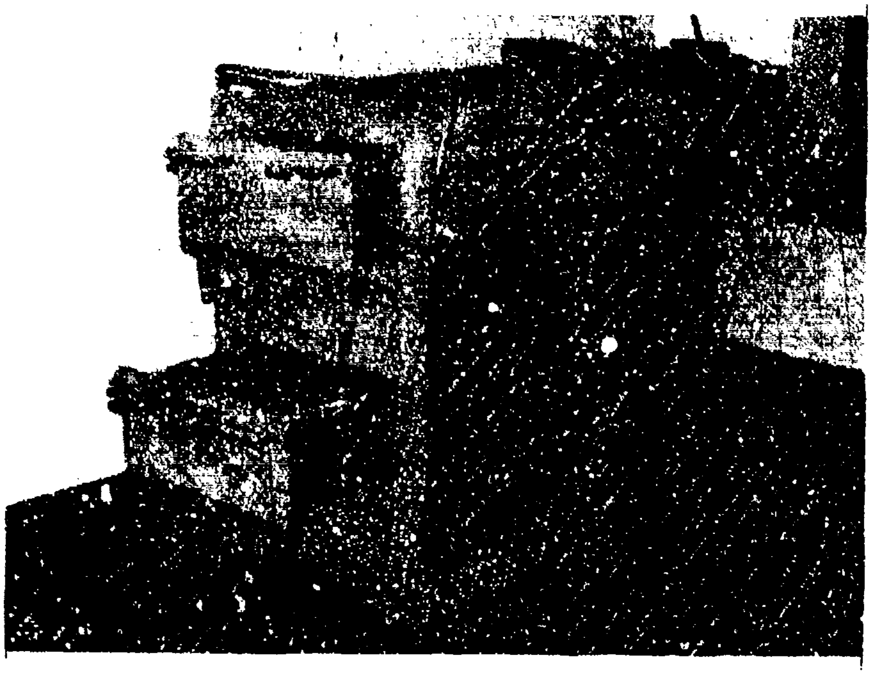
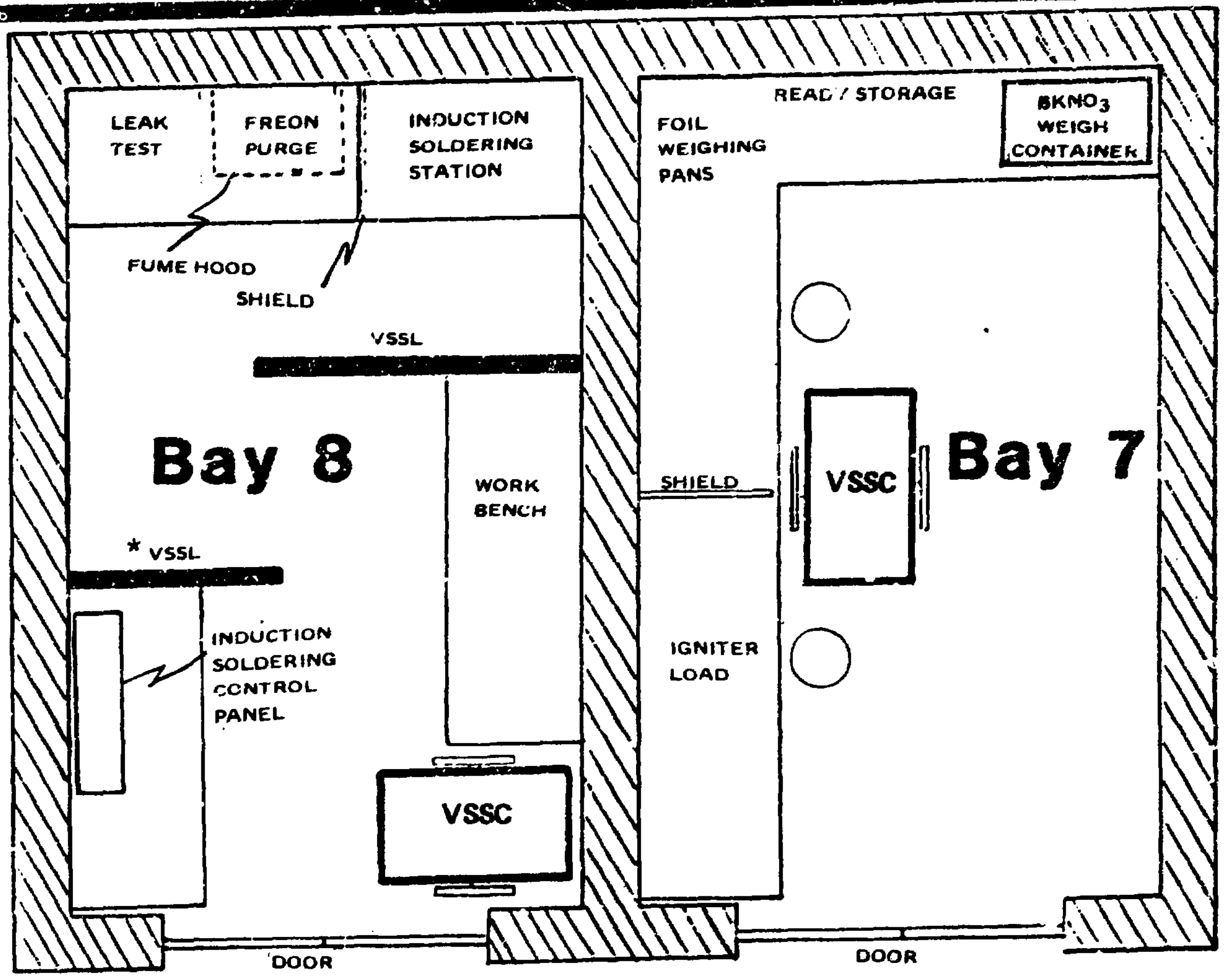


FIGURE 4. VSS CART

FIGURE 5. LABYRINTH WALL ENTRANCE

WORK STATION APPLICATIONS



*Vented Suppressive Shield Labyrinth

FIGURE 6.

AD-P005 323

ULTRA HIGH SPEED DELUGE SYSTEMS

ROBERT A. LOYD

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SAFETY OFFICE

22ND DEPARTMENT OF DEFENSE EXPLOSIVE SAFETY SEMINAR
26-28 AUGUST 1986

ULTRA HIGH SPEED DELUGE SYSTEMS
(DDESB SEMINAR)

1. Pre-primed ultra high speed deluge systems are used to protect personnel, process equipment, and buildings from the fire and thermal hazard presented by munition operations such as weighing, pressing, pelletizing, propellant loading, melting, extrusion, mixing, blending, screening, sawing, granulating, drying, and pouring. An ultra high speed deluge system is designed to apply large volumes of water in an extremely short (milliseconds) period of time. A pre-primed ultra high speed deluge system utilizes the following components:

- Flame detector (ultraviolet or infrared).
- Controller.
- Valve (squib or solenoid operated).
- Piping.
- Nozzles.

2. When a flame detector senses the radiant energy of a flame or fire within its field of coverage, it will respond within milliseconds sending a signal to the controller. The controller in turn sends a signal to the valve to open. Opening of the valve permits line water pressure to be applied to the priming water already in the pipe behind the nozzles, causing water to flow from the nozzles. At the same time, signals are sent to operate alarms and shut down process equipment. Approximately 500 pre-primed ultra high speed deluge systems are used within the Army Ammunition Plant Complex.

3. In Oct 84, the U.S. Army Armament, Munitions and Chemical Command's Safety Office sponsored a seminar on Rapid Action Deluge Systems. The seminar served as a medium for the exchange of information on rapid action deluge systems used in munition production, maintenance, and demil operations. The purpose of this paper is to present the highlights of that seminar, summarize what has occurred since then, and look at areas requiring additional attention.

4. The DOD Ammunition and Explosives Safety Standards (DOD 6055-STD) defines what is an acceptable level of exposure:

- 2.3 psi overpressure or less.
- Fragments less than 58-foot pounds.
- 0.3 calories per sq cm/second or less.

Other publications such as the AMCR 385-100 (AMC Safety Manual), NAVSEA OP 5 (Ammunition and Explosives Ashore), DOD 4145.26-M (Contractor's Safety Manual), MIL-HDBK 1008 (Fire Protection for Facilities Engineering, Design, and Construction), and the National Fire Codes also provide guidance on ultra high speed deluge systems.

5. The hazard to be protected must be accurately defined. The following factors should be considered.

- Quantity of exposed material.
- Initiation sensitivity.
- Heat output.
- Rate of burning.
- Potential ignition and initiation sources.
- Personnel exposure (including protective clothing).
- Frequency of operations.
- Munitions configuration.
- Process equipment and layout.
- Building design and construction.

6. A hazard analysis should be prepared defining the hazard in terms of hazard severity and hazard probability. The factors listed above should be considered. This could be either qualitative or quantitative. MIL-STD 882 (System Safety Program Requirements) and other publications provide guidance on the preparation of hazard analysis. A potential fire and/or thermal hazard whose level of risk is unacceptable (as determined by the DOD Component) should be mitigated by an ultra high speed deluge system. Once the hazard has been accurately defined, the system can be properly designed.

7. Response time criteria should be realistic, and defined in a manner that will permit meaningful testing of the completed installation to ensure the performance criteria was met. It must be recognized that the bigger the system, the longer the response time. Response time criteria and methods of measuring it will be discussed in more detail later.

8. The water density required will depend upon the type, quantity, and configuration of energetic material involved, process layout, and whether the goal is extinguishment, prevention of propagation, prevention of injury, or a combination of these. 0.5 GPM/ SQ FT is a commonly used density for preventing propagation and structural damage. The protection of personnel and process equipment as well as the extinguishment of pyrotechnic fires requires significantly higher density rates. These may be as high 3.0 GPM/SQ FT for area converage or 50 GMP/nozzle for point of operation coverage. Tests have shown that fires involving some pyrotechnic materials being mixed require a water flow of 200 CPM or more to extinguish. Other papers will discuss the extinguishment of pyrotechnic material fires.

9. An estimate of the maximum flow rate and pressure required by the deluge system should be made to determine water supply requirements. The capabilities of the existing water supply and distribution system to meet these requirements should evaluated. A static pressure of 45 to 50 PSI at the building is needed. If the required flow rate and pressure is not adequate, arrangements must be made to provide it. The water pressure required for proper functioning of an ultra high speed deluge system must be available instantaneously, usually from an elevated tank or pressure tank. The instantaneous flow cannot be produced by starting a fire pump or jockey pump; however, a fire pump can be used to provide the required flow and pressure after the system has started to operate. Response time is directly related to water pressure. For most applications, the water supply should have a duration of at least 15 minutes. Water supply requirements for other deluge and sprinkler systems must also be considered. Since fires involving munitions are not normally fought, no allowance is required for fire department hose lines. However, the need for hose lines to protect nearby buildings for fires involving Class 1.3 and 1.4 material and during cleanup should be considered.

10. Two types of detectors are commonly used in ultra high speed deluge systems - ultraviolet and infrared. The ultraviolet (UV) detector senses electromagnetic energy in the UV spectrum. UV detectors are best suited for area and point of operation coverage. The infrared (IR) detector senses electromagnetic energy in the IR spectrum. IR detectors are best suited for use in closed process equipment, vessels, and covered conveyors, and operations shielded from natural and artificial light sources. The detectors should be constant scanning and capable of responding and signaling when a flash or flame is detected. IR detectors respond more quickly than UV detectors and can usually see through a greater degree of contamination (either on the lens or in the atmosphere). IR detectors can be used in open areas, but to eliminate false activations, the signal from the detector must be processed (filtered). This increases response time.

11. In the future, we can expect to see dual IR-UV detectors and dual IR-IR detectors which will look at two separate bands of IR and/or UV radiation. There will also be cross-zoning and matrixing of detectors. This requires a combination of detectors to see a fire or flame before the controller activates the deluge system.

12. To establish and maintain an acceptable level of deluge system performance and minimize problems such as false activations, the following items should be considered:

a. People, communication, and training.

(1) The technical organization responsible for deluge systems must be identified and maintained to ensure deluge systems are adequately designed, installed, and maintained. Army ammunition plants that have established and maintained such a group have reduced their problems with false activations and problems with deluge systems.

(2) Continuity with outside agencies involved with deluge system design, installation, and maintenance should be maintained.

(3) Training of technicians and engineers is vital. They must be sent to vendor schools on a periodic basis to keep abreast of new developments and changing technology.

(4) Transfer of information between using installations and vendors is vital so they can learn from each other's experience.

b. Design and installation.

(1) The pipe diameter, length, number of bends, and friction coefficient contribute to the volume of water that can be transported at an effective pressure through the piping system. Pipe runs and bends should be kept to a minimum, and all horizontal runs should be sloped at least 3/4 inch per 10 feet of run, with air bleeders at all high points. Removal of all trapped air is very important. An air pocket of 5 percent of the total system volume can increase response time by 100 percent. The main water supply line and pilot line (for solenoid operated valves) should have strainers.

(2) Specifications and contract documents should not go into detailed designed of the system, but should clearly define the performance criteria and how they will be measured. These should include:

(a) Detection system.

- Areas to be viewed.
- Source of flash or flame to be detected.
- System logic required.
- Supervisory requirements.
- Testing requirements.

(b) Extinguishing system.

- Area to be protected.
- Water application rate or density.
- Testing requirements.

(c) Other needed information.

- Approximate location of connection to water supply system.
- Water supply line layout and valve locations.
- Location of control panel.
- Available static and residual water pressure (at the minimum required flow rate).

- Need for emergency power.

- Remote signal requirements for alarm systems and process equipment shutdown.

- Required response time.

(3) Failure to follow vendor guidelines during design, installation, and maintenance causes an increase in false activations and related problems.

(4) Limit the overall size of the system (both detectors and nozzles) to smallest practical size possible. This should be below the vendor recommendation maximum. This tends to increase system stability and minimizes false activations and related system problems as it degrades through normal aging and during layaway.

(5) Design changes should be made vary cautiously and field tested on a prototype system. Because there are so many variables, this permits the evaluation of one or two variables at a time.

(6) A complete set of detailed shop drawings, hydraulic calculations, operating instructions, and similar material should be provided by the contractor.

(7) A component Government inspector should verify the deluge system is being installed IAW contract requirements.

(8) Controllers should be located in separate enclosures to reduce false activations due to RF energy generated by other electrical devices.

(9) The controller must be programmed for the number of detectors to be used. Failure to do so can affect the internal test features and reliability of the controller.

(10) Process equipment should be interlocked through controller fault circuitry.

(11) Conduit carrying detector cable and detector tubes should be sealed. Failure to do so will permit moisture in the detectors and conduit causing false activations and system problems.

(12) Automatic inspection features built into detectors and controllers are cost effective because they help identify problems and faults in a more timely manner and mandate a better preventive maintenance policy.

(13) UV detectors for ultra high speed deluge systems should be located to provided two levels of protection. One or more detectors should be placed as close as physically possible to the most likely source(s) of ignition. They should be located so the detector's field of view is not blocked by shield, equipment, or personnel. One or more additional detectors should be located to provide general area coverage of the cubicle or bay, on the assumption that an ignition could occur at other points within the area. UV and IR detectors are optical devices, and as such respond to the atttenuation laws of optics, doubling the distance between the detector, and the flame will reduce the radiation perceived to one fourth; conversely, reducing the distance by one half results in four times more radiation to the detector.

(14) UV detectors are sensitive to weld arcs, lightning, x-rays (gamma radiation), cosmic and background radiation, and high electrostatic charges. They should be located away from the horizontal plane, nor should they be aimed toward doors or windows.

(15) UV radiation will not transmit through smoke, water vapor, acetone, regular glass, plexiglass, or oil.

(16) Detector cabling should be the shielded type and placed in conduit separated from all other wiring. Ensure that detector cabling and cable shielding are installed and grounded according to vendor specifications. Proper cable installation and grounding minimize system problems and false activations.

(17) Deluge valves should be located as close as possible to critical nozzles to reduce response time.

(18) Critical nozzles should be located as close as possible to the hazard. The water travel time from the nozzle to the target is the longest component of response time.

c. Maintenance and testing procedures.

(1) A good preventive maintenance program is required. Experience has shown that increasing the time period beyond 4 to 6 weeks results in a significant increase of false activation and other system problems. A tri-service manual entitled Maintenance of Fire Protection Systems (TM 5-695/NAVFAC MO-117/Air Force AFM 91-37) provides guidance on the inspection and testing of fire protection systems. The following items should be considered when establishing maintenance procedures:

(2) System checks.

- Measure all voltages.
- Pull all controllers and check for loose wires and or relays.
- Clean all dirt and debris from console.
- Relamp console.
- Spotcheck conduit fittings for moisture and or loose wire nuts.
- Spotcheck squib operated valves for dampness or moisture (wet primers).
- Check OS&Y Limit Switch.

(3) Detectors.

- Remove each lens and clean.
- Remove each barrel and check grounding springs, when used.
- Tighten each terminal screw in sensors.
- Clean and inspect all optical integrity rings.
- Check for moisture and or corrosion inside sensor housings.
- Check each sensor for proper alignment.
- Check housing for continuity.
- Relamp all controllers.
- Reactivate system and check for problems.

(4) Flow tests should be conducted.

- Annually for active systems.
- After major maintenance or modification.
- After reactivating an inactive system.

13. There is no common agreement on the definition of deluge system response time. This has caused confusion and prevented the development of a performance type specification. This precludes the effective evaluation of deluge systems. The AMC Safety Manual (AMCR 385-100) defines response time as the time from the sensing of a detectable event to the beginning of the flow of water from the deluge nozzles. This definition is a marked improvement over the definition that appeared in earlier editions of the safety manual. It was previously defined as the time from ignition to a fully developed flow pattern of water being applied to the hazard.

14. In order to more precisely define response time requirements, it is necessary to understand the interrelation between development of an incident and deluge system functions. The following outlines a way of breaking down the fire dynamics and deluge system functions into understandable segments:

a. Ignition Time - T0: Ignition time is defined as the start of ignition. Ignition of an item is defined as self-sustained deflagration.

b. Ignition To Sensing Threshold Time - T1: Ignition to sensing threshold time is defined as the time from ignition until the buildup of energy reaches the sensing threshold of the sensor. This is dependent upon the configuration of the item being protected. For example, the ignition of propellant from the bottom of a hopper may require more than a second to reach the surface of the propellant where it can be sensed by a detector. If ignition occurred on the surface, the ignition to sensing threshold period would be much less - in the millisecond range.

c. Ignition To Sensor Response Time - T2: Ignition to sensor response time is defined as the time from ignition to transmission of the signal to the controller.

d. Ignition To Controller Response Time - T3: Ignition to controller response time is defined as the time from ignition to transmission of signal to deluge valve squib or solenoid.

e. Ignition To Valve Opening Time - T4: Ignition to valve opening time is defined as the time from ignition to the opening of the deluge valve permitting water to flow.

f. Ignition To First Water at the Nozzle Time - T5: Ignition to first water at the nozzle is defined as the time from ignition to the first flow of water from the critical nozzle(s). This is usually the nozzle(s) closest to the hazard or as determined by a hazard analysis.

g. Ignition To First Water on Target Time - T6: Ignition to first water on the target is defined as the time from ignition to the first drops of water to strike the target from the critical nozzle(s). There is usually an initial stream of water, followed by a break in the flow, followed by a full flow pattern.

h. Ignition To Full Flow Water On Target Time - T7: Ignition to full flow water on target is defined as the time from ignition to a fully developed spray of water strikes the target area.

i. Extinguishment Time - T8: Ignition to extinguishment is defined as the time from ignition to termination of the deflagration.

15. Deluge system response time should be redefined as Total Response Time. This is the total time lapse from sensor response to full flow of water on the target area (T2-T7). Total Response Time should then be divided into two segments - Electrical/Mechanical Response Time (T2-T5) and Water Travel Time (T5-T7). The total response time must be considered when designing deluge systems. However, for specifying performance in contract documents, only Electrical/Mechanical Response Time should be used. This will also provide a baseline for checking system response time during the annual flow tests and after a system has been inactive for an extended period of time, or a system has been modified.

16. Two methods frequently used to check response time of ultra high speed deluge systems are a digital timer and a high speed video recording system. The digital timing system consists of a circuit connected to the digital timer, a flow switch, valve solenoid or squib, detector, and controller. The high speed video system consists of a high speed camera and recorder. The camera can record a frame every 8 milliseconds. The digital timer can only measure Electrical/Mechanical Response Time, is well suited for use by maintenance technicians at ammunition plants, and is much less expensive than the high speed video system. The high speed video recording system is very expensive to purchase ($35-80,000) and requires a skilled technician to use. It is the ideal tool for determining total system performance, compliance with performance criteria specified in contract documents, evaluating new or modified systems, and determining Total Response Times.

17. Presently, deluge systems are assembled rather than designed. There is some engineering skill, some black art, and lots of luck involved. Once it has been decided to install a deluge system, design is accomplished by selecting the components based on personnel experience and position them as best as possible to deal with a hazard that is not completely defined. Many of these problems could be solved by developing a computer model for ultra high speed deluge systems. The variables listed in paragraph 5 and those listed below should be considered:

- Water flow rate.
- Time to detection.
- Extinguishment time.
- Water pressure.
- Pipe size.
- Pipe configuration.
- Number of nozzles.
- Nozzle design.
- Deluge valve location.
- Pressure rise of the energetic material.
- Change in temperature.
- Process equipment layout and shape.
- Packing density of the energetic material.
- Volume of energetic material.
- Heat of combustion.
- Grain shape and size.
- Water travel distance from the nozzle to the hazard.

18. The need for a "portable" deluge system has been identified by several Army commands and is being evaluated by the U.S. Army Armament, Munition and Chemical Command's Safety Office. Two configurations appear to be needed. One that is completely self-contained with its own UV detectors, nozzles, and water supply. The other would have the detectors and nozzles but would require water from the building water system. These systems could be used where the installation of a permanent deluge system is not feasible or cost effective. The protection provided by a "portable" deluge is very limited and is not a

substitute for permanently installed systems. Inspection, maintenance, and renovation operations taking place in depots and field locations would be prime candidates for portable deluge systems. A presentation by Automatic Sprinkler, Inc., will deal with portable deluge systems in more detail.

19. The following areas require additional work and effort:

- Computer modeling.
- Development of a "portable" deluge system.
- Technical guidelines and performance specifications.
- Performance evaluation procedures.
- Determining causes of false activations.
- Information exchange between vendors and users.
- Evaluation of new deluge system technology.

20. These actions can best be accomplished by:

- Updating technical manuals and regulations.
- Formation of an informal working group.
- Holding seminars and workshops on a regular basis.
- Having a central organization be responsible to monitor developments, oversee research programs, develop a data base, and pass information to users and vendors.

21. Other papers presented during this seminar will deal with various aspects of deluge systems in more detail.

22. The technical reports in Appendix A and the references in Appendix B were utilized in the preparation of this paper. Additional technical material was provided by the following persons:

a. Mr. Louis Joblove and Mr. Manuel Avelar, Amman and Whitney Consulting Engineers.

b. Mr. James Brazell, Mr. Stanley Straker, and Mr. Mervin Opel, ICI Americas, Inc., Indiana AAP.

c. Mr. Gene Burns, Day and Zimmerman, Inc., Lone Star AAP.

23. POC - Robert A. Loyd:

a. HQ, AMCCOM, ATTN: AMSMC-SFP, Rock Island, IL, 61299-6000.

b. AV 793-2975, FTS 367-2975, COM (309) 793-2975.

DELUGE SYSTEM RESPONSE TIME

T0 = IGNITION TIME

T1 = SENSING THRESHOLD

T2 = SENSOR RESPONSE TIME

T3 = CONTROLLER RESPONSE TIME

T4 = VALVE OPENING TIME

T5 = FIRST WATER AT NOZZLE TIME

T6 = FIRST WATER ON TARGET TIME

T7 = FULL WATER ON TARGET TIME

T8 = EXTINGUISHMENT TIME

APPENDIX A

TECHNICAL REPORTS ON DELUGE SYSTEMS

1. Design of a Deluge System to Extinguish Lead Azide Fires, No. AD-E400 204, Aug 78, approved for public release (APR).

2. Evaluation of Pyrotechnic Fire Suppression System for Six Pyrotechnic Compositions, No. AD-E401 306, Mar 85, APR.

3. Engineering Guide for Fire Protection and Detection Systems at Army Ammunition Plants, Vol I (Selection and design), No. AD-E400 531, Dec 80, APR.

4. Engineering Guide for Fire Protection and Detection Systems at Army Ammunition Plants, Vol II (Testing & inspection), No. AD-E400 874, Dec 82, Distribution limited to U.S. Govt Agencies only - contains proprietary information.

5. On-site Survey and Analysis of Pyrotechnic Mixer Bays, No. AD-E401 141, Feb 84, APR.

6. Feasibility Study to Develop a Water Deluge System for Conveyor Lines Transporting High Explosives, Tech Rpt No. 4889, Aug 75, APR.

7. Development of a Water Deluge System to Extinguish M-1 Propellant Fires, No. E00 217, Sep 78, APR.

8. Design of a Water Deluge System to Extinguish M-1 Propellant Fires in Closed Conveyors, No. AD-E400 216, Sept 78, APR.

9. Fire Suppression System Safety Evaluation, No. AD-E401 083, Dec 83, APR.

10. Dynamic Model of Water Deluge System for Propellant Fires, No. AD-E400 315, May 79, APR.

11. Deluge Systems in Army Ammunition Plants, prepared by Science Applications, Inc., for the U.S. Army Munitions Production Base Modernization Agency, 30 Jun 81.

12. Minutes of the Rapid Action Fire Protection System Seminar, U.S. Army Armament, Munitions and Chemical Command, 23-24 Oct 84.

Most of these reports can be ordered from the Defense Technical Information Center, Cameron Station, Alexandria, VA, 22314. Their telephone number is AV 284-7633.

APPENDIX B

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A New Explosion Test Facility at NSWC--The 50-Pound Bombproof

by

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ABSTRACT

A new test facility was recently dedicated at the Naval Surface Weapons Center, White Oak Laboratory, Silver Spring, Maryland--a bombproof with a 50-pound TNT equivalent explosive limit. Details of the facility concept, design, and construction will be presented. Before the facility was put into use, a series of validation tests were performed. These tests included test firings over the explosive weight range of 1 to 50 pounds of TNT. The following measurements were undertaken: (1) wall strains, (2) wall displacements, (3) floor vibrations, (4) explosion-produced noise both inside and external to the facility, and (5) gas leakage both into the work areas surrounding the facility and into the atmosphere outside the facility. The results of these measurements will be presented and summarized. Finally, a description of the capabilities and specialized equipment dedicated to this facility will be discussed.

BACKGROUND

The Naval Surface Weapons Center (NSWC) operates several explosion containment test facilities at its White Oak, Maryland site. These facilities range in capacity from a few ounces of energetic material (propellant, pyrotechnics, or explosive) to five pounds of energetic material. All of these facilities are over 30 years old. In the 30-years since their construction, the nature of the surrounding community has changed significantly--from a lightly populated rural area to a moderately--densely populated urban area. No explosion facility at White Oak is more than about 2000 feet from civilian residences.

Since the early 1950's, when the other facilities were constructed, the nature of the experimental programs being conducted have developed to the point where energetic material limits greater than five pounds are required. One of these drivers has been the development and usage of ammonium perchlorate, metallized-type explosives, as well as other highly insensitive energetic materials, which require the firing of larger charge sizes in ever increasing numbers. The tests are required to develop the basic data and knowledge concerning these materials, so that sound judgements can be made as to their suitability for specific weapons applications. This testing requires the full-time, year round usage of any new facility.

After a series of trade-off studies, it was decided that the new facility should be capable of containing the consequences of a detonation of a 50-pound (TNT equivalent) fragmenting charge, at the rate of at least one per week, or any number of smaller detonations. Moreover, because of the nearby urban residential area, the facility should minimize noise and ground shock transmissions to the surrounding areas and also meet all local, state, and federal pollution requirements.

With these and other requirements, the firm of Ammann and Whitney studied and developed the concept for the facility. Their proposal was completed in August 1980.[1] Drawings and specifications were released in 1982,[2] and the facility was accepted on 28 September 1984. Validation testing began shortly thereafter in December 1984, and the official dedication took place in July 1985.

FACILITY DESCRIPTION

The facility, as constructed, consists of an instrumentation and control building with four auxiliary structures. The important building is the instrumentation and control building, and this is what will be described in a subsequent section.

Figure 1 is a plan view of the instrumentation and control building. The building contains a gun room for two guns--a high pressure helium gun and a powder gun, a mechanical room containing all the HVAC (heating, ventilation, and air conditioning equipment), a control room, an instrumentation area, and a blast containment chamber. Figure 2 presents two additional views of the building-- a side view looking north, and a side view looking east.

The heart of the structure is the blast containment chamber. The chamber is octagonal in section and has plan dimensions of approximately 20 x 20 feet, and is 16 feet high. The volume of the chamber is approximately 6200 cubic feet.

The chamber is constructed of reinforced concrete having a minimum compressive strength of 4000 psi at 28 days. The reinforcing material consists of deformed billet steel bars conforming to ASTM A615 grade 60 except grade 75 is used for size 11 bars. The minimum concrete thickness is five feet. The blast chamber interior is lined with removable one inch thick steel fragmentation shields. The blast chamber is completely isolated from the surrounding building. In addition, efforts were taken to decouple the chamber from the soil beneath it. The chamber rests on a layer of polystyrene. Below the polystyrene is a layer of lean concrete, which, in turn, is supported by a four-foot layer of crushed rock. Below the crushed rock is natural soil.

The outside of the blast containment chamber is covered with corrugated metal siding attached to the chamber by steel channels and bolts which are embedded in the concrete and anchored around the reinforcement. This metal siding acts as a spall shield to protect personnel from flying fragments produced by the disengagement of portions of the concrete cover on the exterior of the five foot thick containment walls, should it ever occur. (No evidence of this has occurred to date.)

Blast pressure relief within the chamber is provided by an exhaust stack above the chamber roof. A muffler is attached to this stack to achieve noise attenuation.

Access to the chamber is via a single, hydraulically-operated door. The door is not solid--rather, it has an inner face (towards the inside of the chamber) of three inch thick high strength pressure vessel steel alloy. The outer surface is a thinner version of the same alloy. The total weight of the door is approximately 9600 pounds. The door hinges are only intended to support the door weight--not the blast loading. The blast loads are transferred from the door into the door frame. The frame is constructed of structural steel and cast into concrete. Steel stiffener plates and reinforcing bars welded to the frame provide positive anchorage. The door is sealed by a continuous elastomeric gasket adhered into a groove with a machine finish.

FACILITY VALIDATION

After the facility was accepted, but before it was placed into operational use, it was determined that a series of validation tests should and would be performed. These tests were designed with several functions in mind:

(1) To determine if the building could, indeed, safely contain the effects of the detonation of up to 50 pounds of TNT.

(2) To determine if the detonation of materials within the blast chamber produced any adverse effects either on personnel or equipment contained within the facility.

(3) To determine, as far as possible, if the detonation of materials within the blast chamber produced any adverse effects on the environment surrounding the building.

With these goals in mind, a series of TNT charges with weights ranging from one to 50 pounds were detonated and their effects in, on, and around the facility were measured. The TNT charges were right circular cylinders, placed on a wooden table, four feet above the floor in the center of the chamber.

The measurements undertaken included strain in the exterior walls of the chamber, wall displacement, floor motion, carbon monoxide levels in the instrumentation area, and sound pressure levels both inside the building and at several locations external to the building. These results are reported in detail in NSWC TR 85-385[3] and will be summarized below.

Wall Strain

Strain measurements were made at three locations on the exterior walls of the blast containment chamber. Each position used two gauges, measuring vertical and horizontal strain. Each gauge was mounted directly on the concrete wall. Figures 3, 4, and 5 summarize the measured strain data. The maximum strain recorded was approximately 350 micro-strain on the 30-pound shot. On the 50-pound, it dropped back to about 200 micro-strain.

Wall Transient Displacements

Transient wall displacements were measured on all four blast containment chamber walls. The transducers were capable of measuring ±0.250 inch of displacement, with a resolution of 0.001 inch. Figure 6 summarizes the results obtained for all four walls. The maximum transient displacement was approximately 0.06 inches. All four walls exhibited an interesting phenomena. The displacements produced by the 30-pound charge were considerably less than those produced by either the 20- or 50-pound charges.

Floor Vibrations

Floor motion was monitored in one location in the instrumentation room--10 feet from the north wall of the blast chamber. A three component velocity gauge was utilized. Measurements were made in the vertical, transverse (east-west), and radial (north-south) directions. Figure 7 presents the peak-to-peak velocities recorded for each charge size. Figure 8 presents the predominant frequencies associated with the motions presented in Figure 8.

Noise Measurements

Sound pressure level measurements were made at several locations both inside the facility and on the grounds outside. Within the instrumentation and control rooms, both time-resolved pressure instrumentation and peak holding meters were utilized. Peak holding meters were used outside the facility. All peak holding devices were set to record peak flat sound pressure levels. Figure 9 shows the measurement locations inside the chamber. Figure 10 presents the results recorded at each location. Figure 11 presents similar results recorded outside the facility. Figure 12 presents pressure-distance information for the 50-pound charge size. The predominant frequency for the noise recorded in the instrumentation area was 100-170 Hz.

Carbon Monoxide Levels

Carbon Monoxide (CO) gas concentration levels were monitored both in the control room and in the instrumentation area. Within the control room, carbon monoxide levels above background were recorded only on the 20-pound shot. Even here, the CO level only went up to 10 parts per million (ppm). Excessive (greater than the allowed level of 50 ppm) levels of CO were recorded in the instrumentation area on both the 30- and 50-pound shots. The CO levels recorded in the instrumentation area are shown in Figure 13. Once the chamber and instrumentation areas were properly vented, the recorded levels went down to zero.

VALIDATION TEST SUMMARY

These validation tests showed that, indeed, the new facility could safely contain the effects of a 50-pound TNT detonation. Based on the measurements, it is felt that equipment within the instrumentation area or personnel within the control room, should suffer no adverse effects from a 50-pound detonation. The amount of pollutants (noise and gaseous) released into the surrounding environment are in total compliance with all existing environmental regulations.

FACILITY CAPABILITY/INSTRUMENTATION

Data Collection:

The Building 327 complex is equipped with various data collection systems including:

1. Lecroy Digital Oscilloscopes
2. Nicolet Digital Oscilloscopes
3. Tektronix Logic Analyzers
4. HP7912, and HP7612 Digitizers

All of these systems are connected/controlled by an HP9020 computer system. The computer system consists of eight stations with a printer, plotter and terminal emulation/communication capabilities. This computer is used as a controller, word processor, database filing system and terminal emulator. It is also used to perform data analysis and hydrocode work.

The following equipment either has been or is currently being installed in the Building 327 complex.

Laser Interferometer - Visar - The Visar interferometer uses doppler shifting of coherent laser light off of a reflective surface in order to establish the acceleration and velocity profiles of the reflective surface. The reflective surface may be a gas gun projectile, an aluminized free surface of an explosive, or a kapton flyer on an insensitive high explosive "slapper" detonator.

Laser Interferometer - Fabry Perot - An inexpensive version of the "Visar," the Fabry Perot will be used with a fiber optic bundle to record laser light shifts on an image converter streak camera.

Microwave Interferometer - The microwave interferometer works similar to a laser interferometer, the only difference is the wave length of the probe radiation. Explosives and propellants are largely invisible to microwaves; however, microwaves are easily reflected and doppler shifted by a detonation front. Thus, burn rates and detonation velocities can be directly determined.

Laser Raman Spectroscopy - This technique will be used to determine what types of free radicals and ions are formed within the detonation zone.

Laser Schlieren Photography - Laser schleiren methods will be used to photograph shaped charge jet stretching and erosion within a water cavity. The coherent, single band light which is cavity-dumped will, theoretically, allow closer study of jet/water interactions.

Imacon 790 - This image converter camera uses photo-multiplier tubes to photograph low light level events at 20 million frames/sec (16 frames may be recorded) in the framing mode and 1 mm/ sec in the streak mode. It can also be used in conjunction with fiber optic probes and laser interferometry.

Three other types of optical cameras will also be available: Cordin 375, Cordin 121, and Cordin 132. The Cordin 375 can record a total of 500 frames at rates up to 200,000 frames/sec. The Cordin 121 can take up to 25 frames at rates up to 2.5 million frames/sec. The Cordin 132 is a 70-mm format streak camera.

Flash X-rays - The explosive facility is equipped with several 300 KV and one 2.3 MeV flash x-ray tubes for radiography. These are used to study fragmentation patterns, shaped charge jets, and other events with contrasting density gradients.

SUMMARY

The new 50-pound explosion test facility at NSWC has become a unique asset both to the Navy and the free world. Its ever-increasing capabilities will place it at the forefront of detonation research.

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2. "Drawings and Specifications for Explosive Test Facility at the Naval Surface Weapons Center, White Oak, Maryland," Ammann & Whitney, World Trade Center, New York, New York, March 1982.

3. Swisdak, M. and Peckham, P., "Validation Tests in Building 327 - 50-Pound Bombproof," NSWC TR 85-384, 30 October 1985.

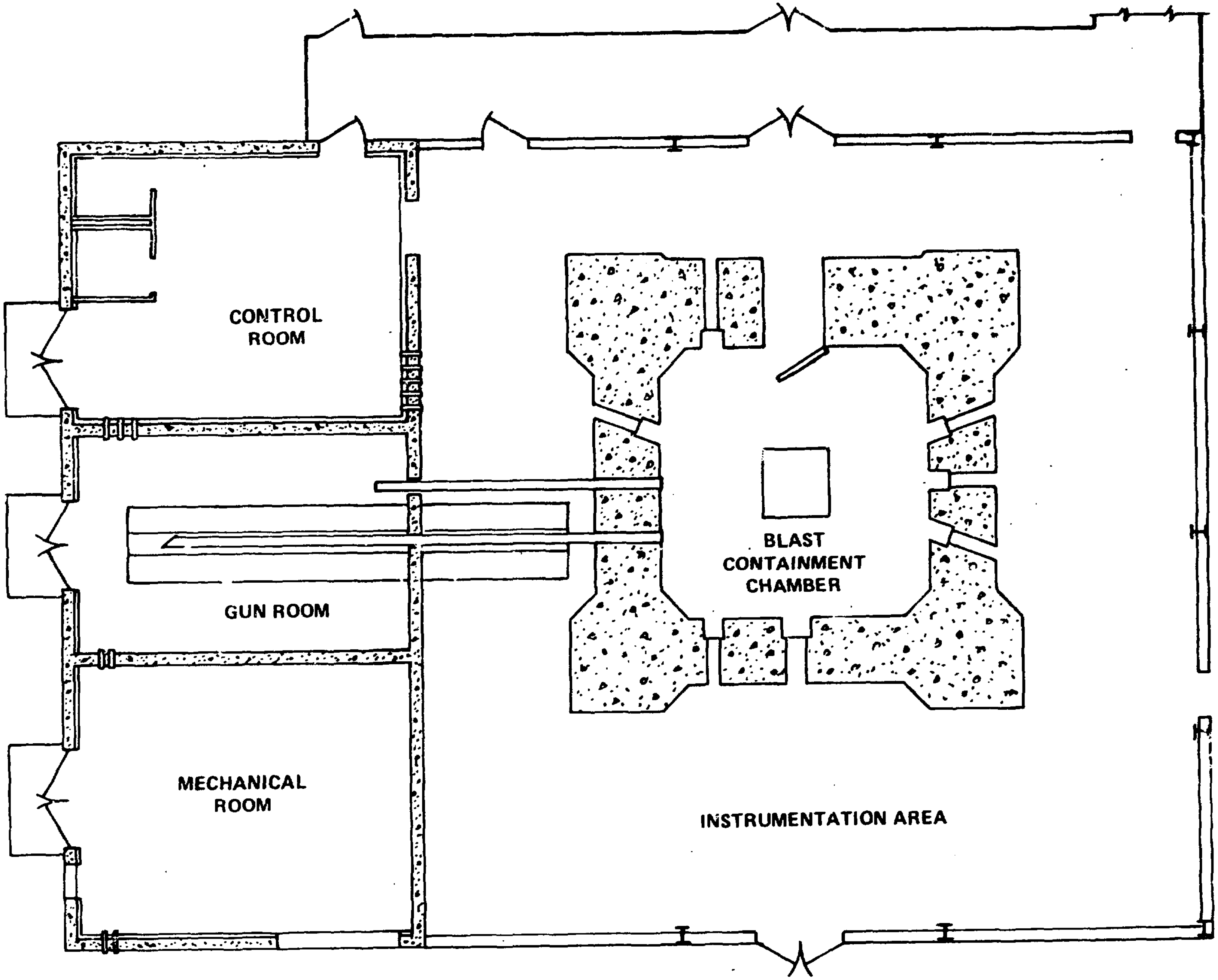
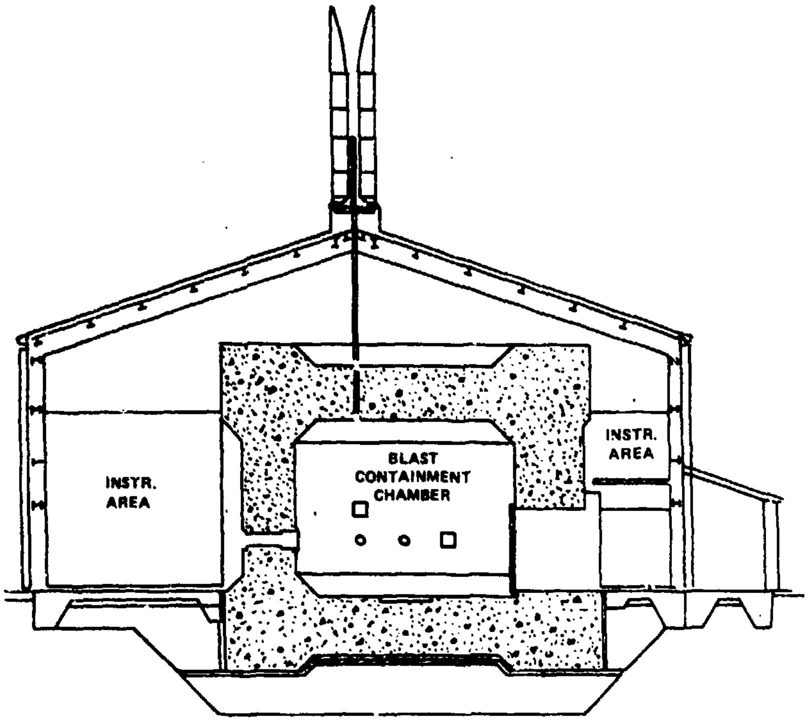
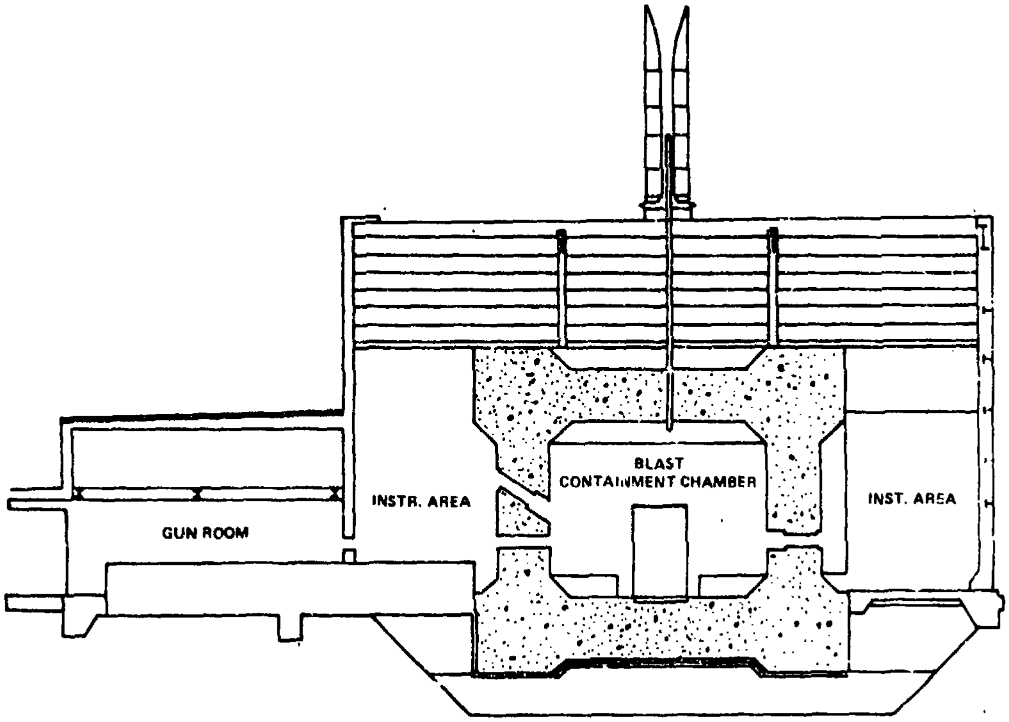


FIGURE 1. BUILDING 327, PLAN VIEW



BUILDING 327, SIDE VIEW, NORTH



BUILDING 327, SIDE VIEW, EAST

FIGURE 2. BUILDING 327- - SIDE VIEW, NORTH & EAST

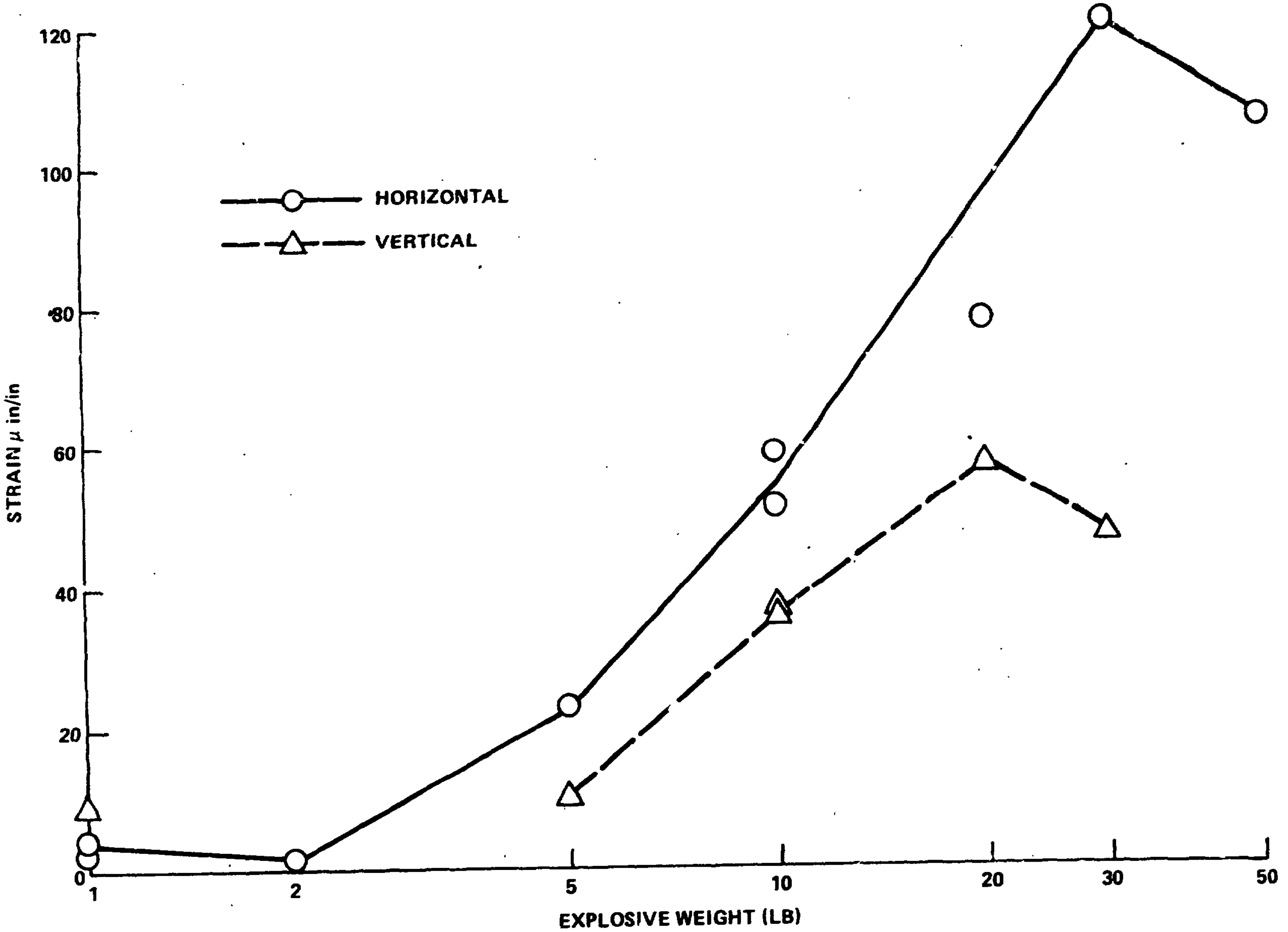


FIGURE 3. STRAIN VERSUS EXPLOSIVE WEIGHT, EAST WALL

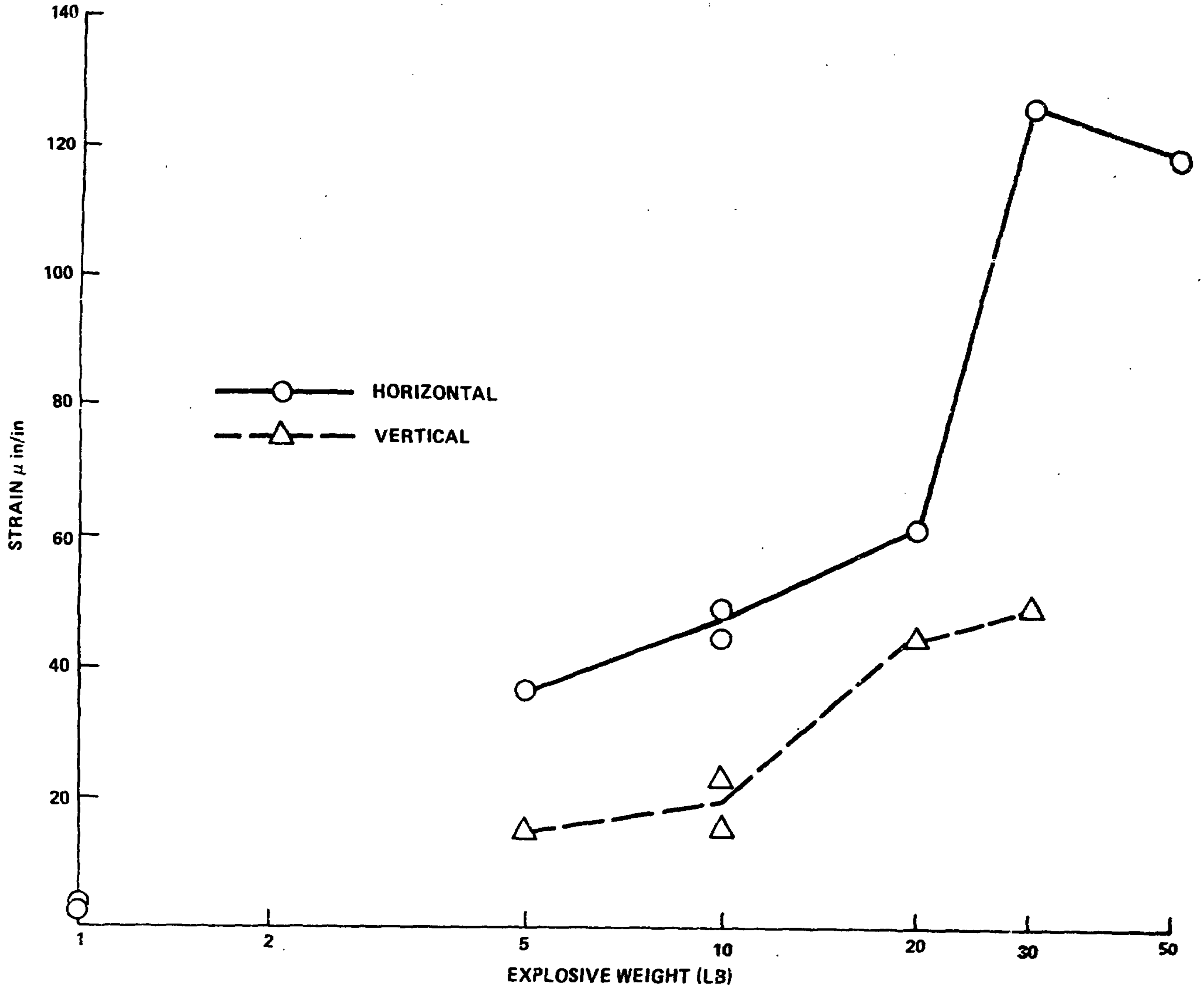


FIGURE 4. STRAIN VERSUS EXPLOSIVE WEIGHT, NORTH WALL

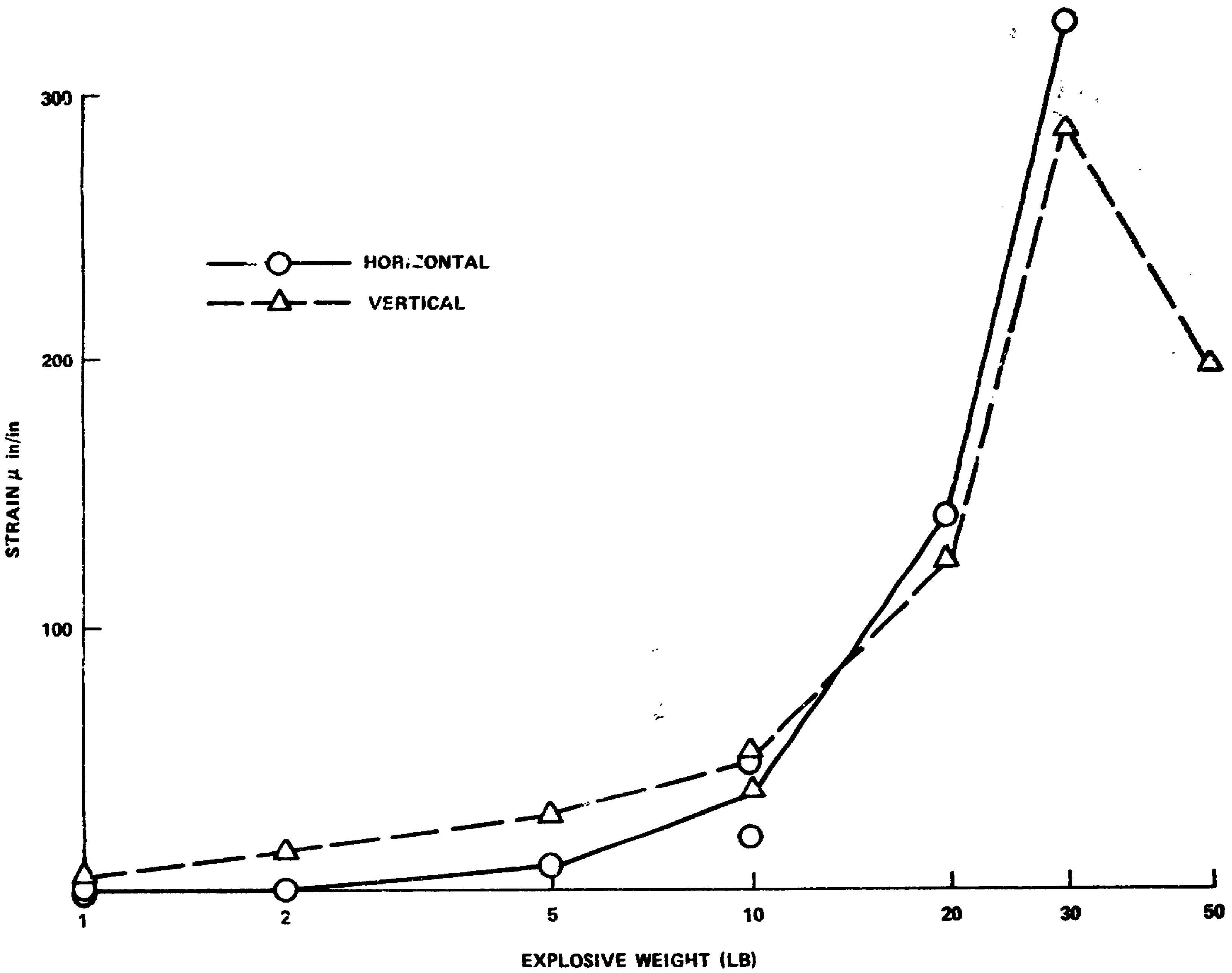


FIGURE 5. STRAIN VERSUS EXPLOSIVE WEIGHT, SOUTH WALL

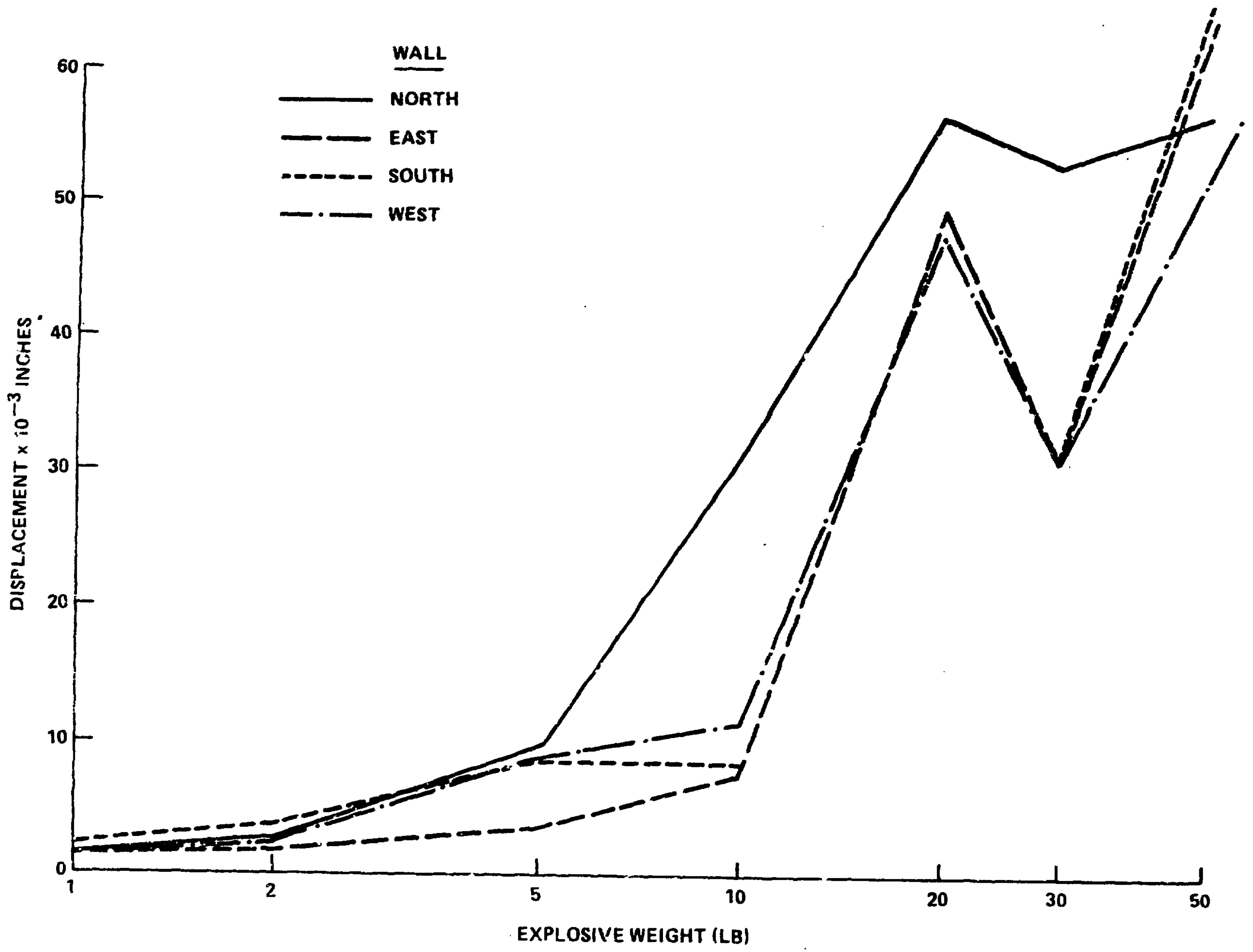


FIGURE 6. MAXIMUM WALL DISPLACEMENT VERSUS EXPLOSIVE WEIGHT

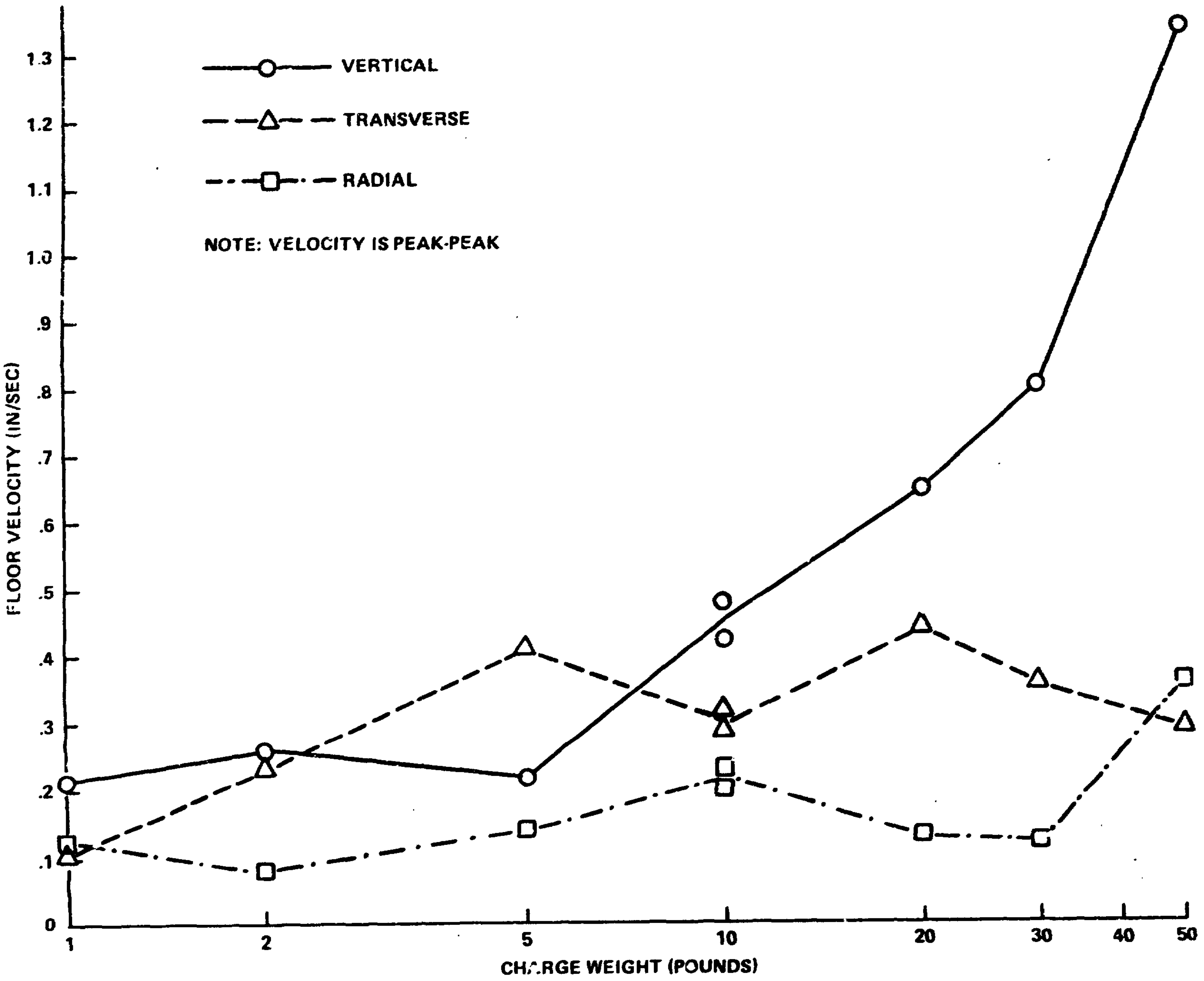


FIGURE 7. FLOOR VELOCITY VERSUS CHARGE WEIGHT

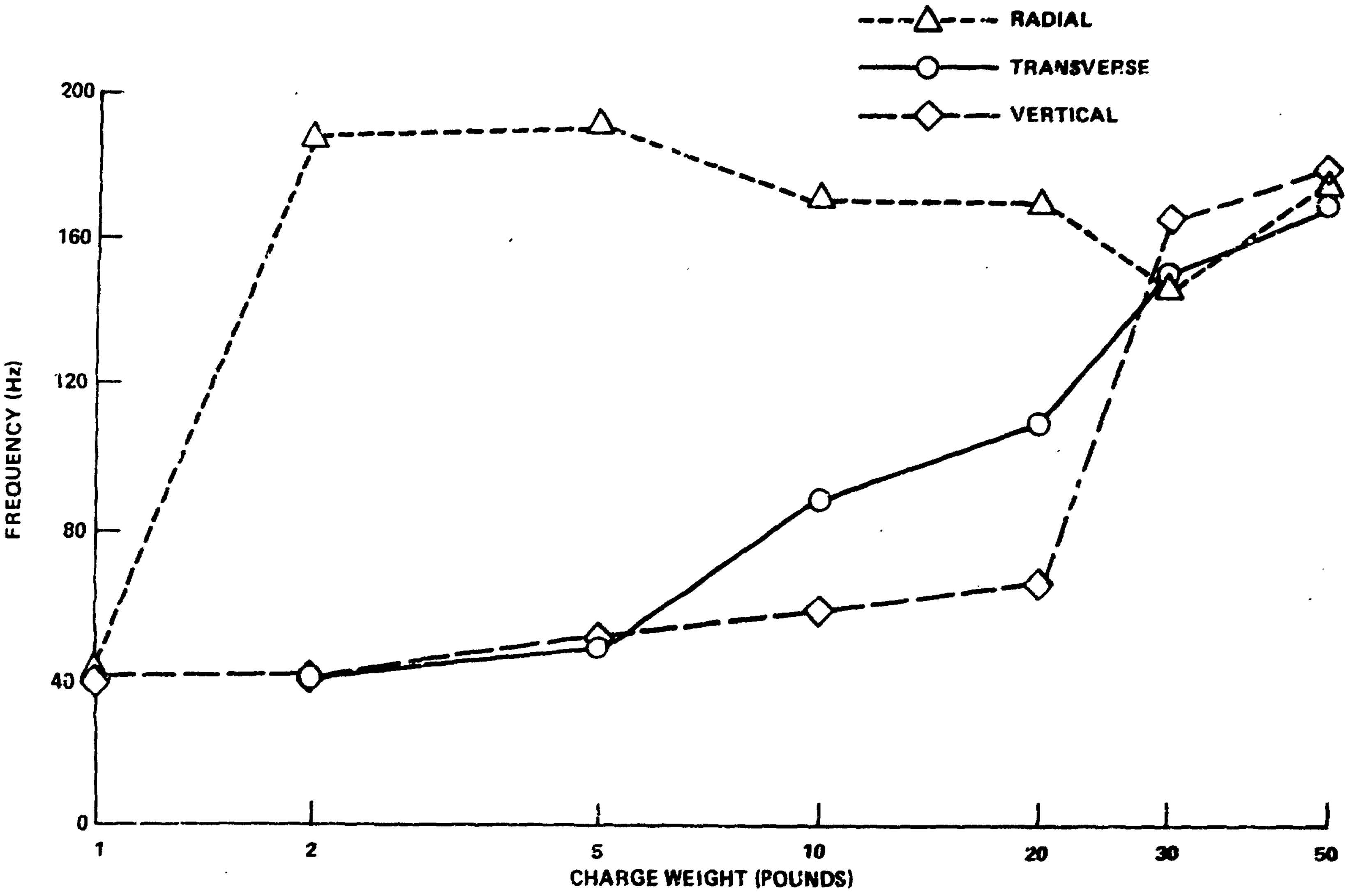


FIGURE 8. FLOOR MOTION FREQUENCY VERSUS CHARGE WEIGHTBUILDING

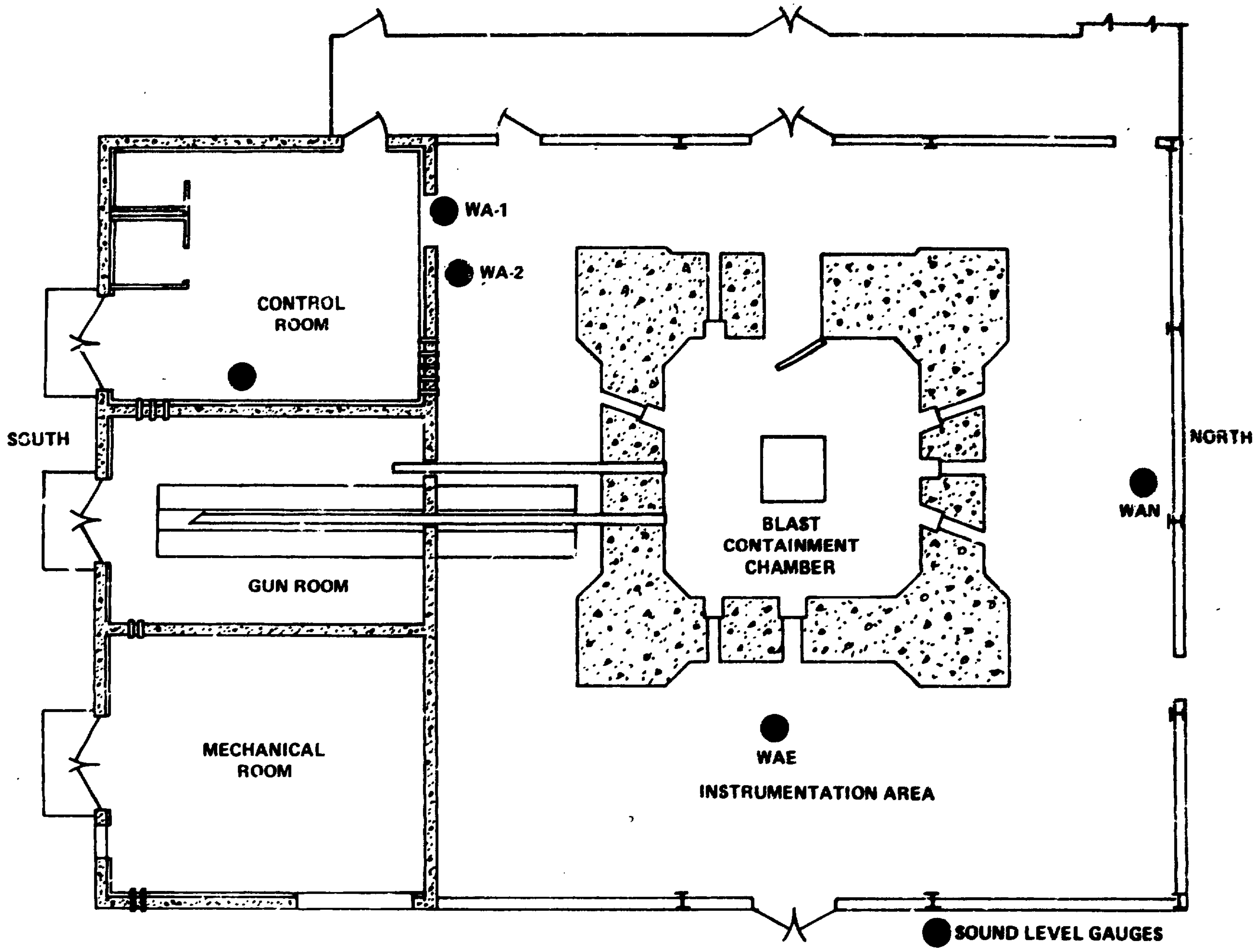


FIGURE 9. LOCATION OF SOUND LEVEL GAUGES

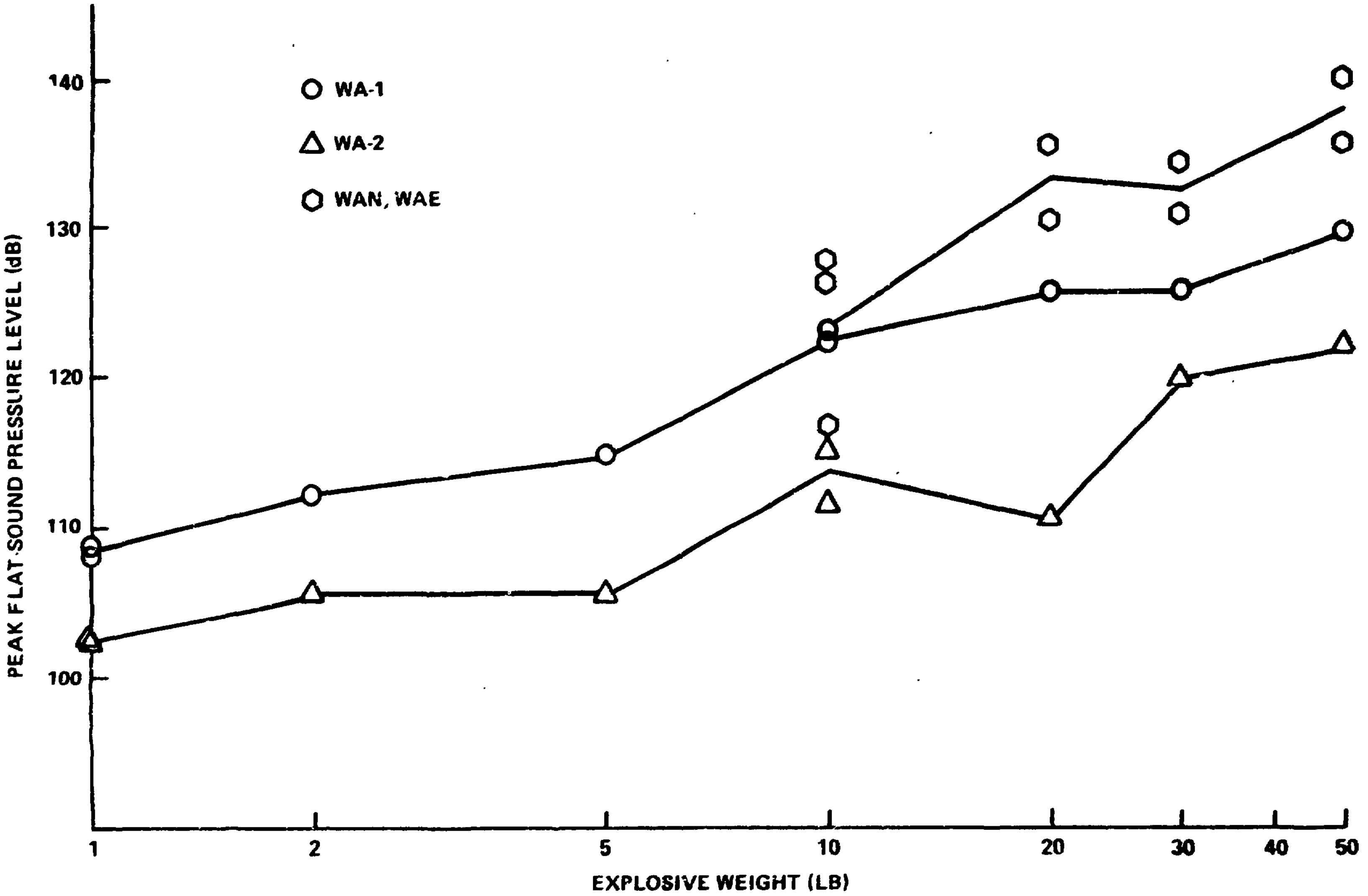


FIGURE 10. SOUND LEVEL VERSUS WEIGHT IN WORK AREA AROUND BLAST CHAMBER

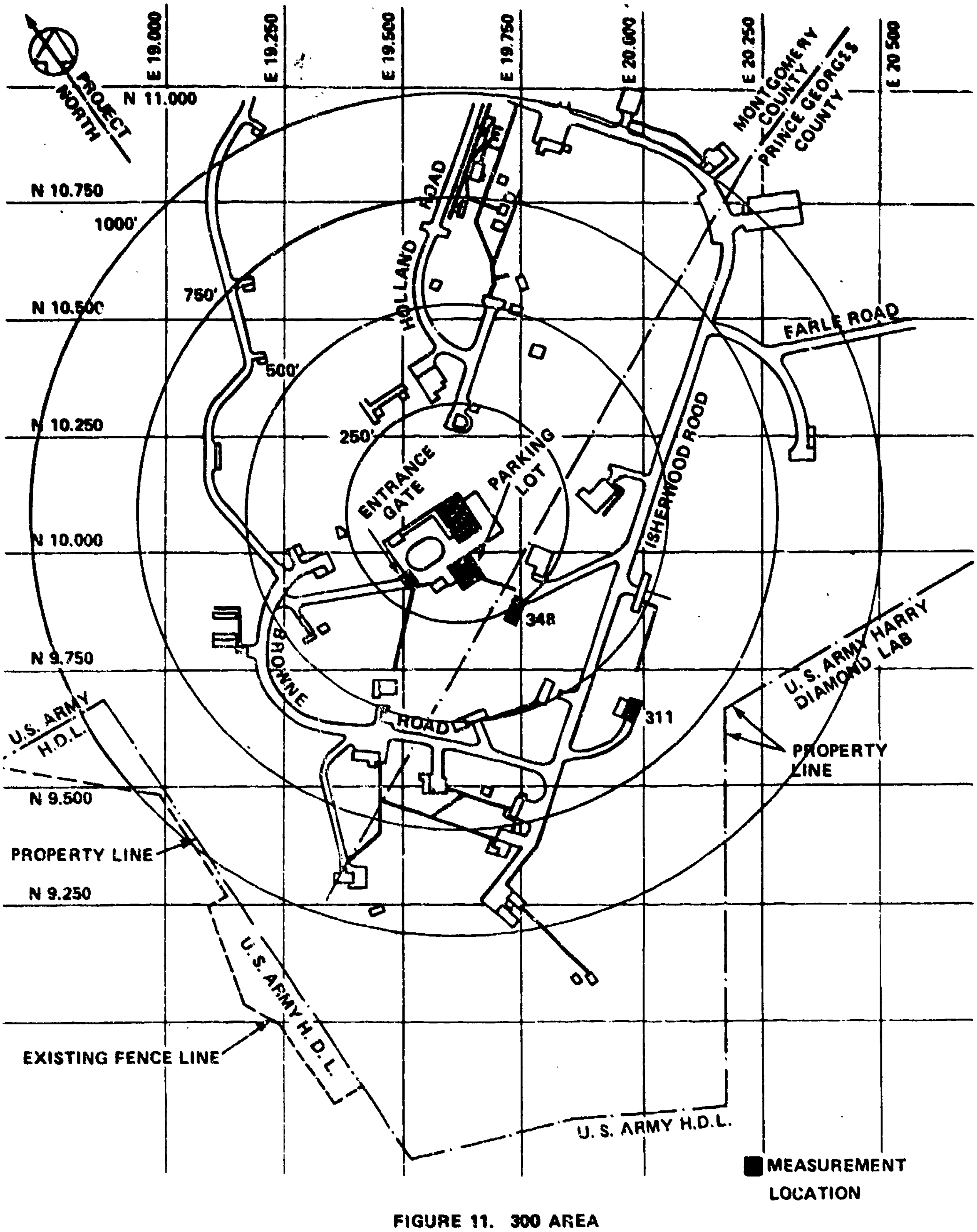


FIGURE 11. 300 AREA

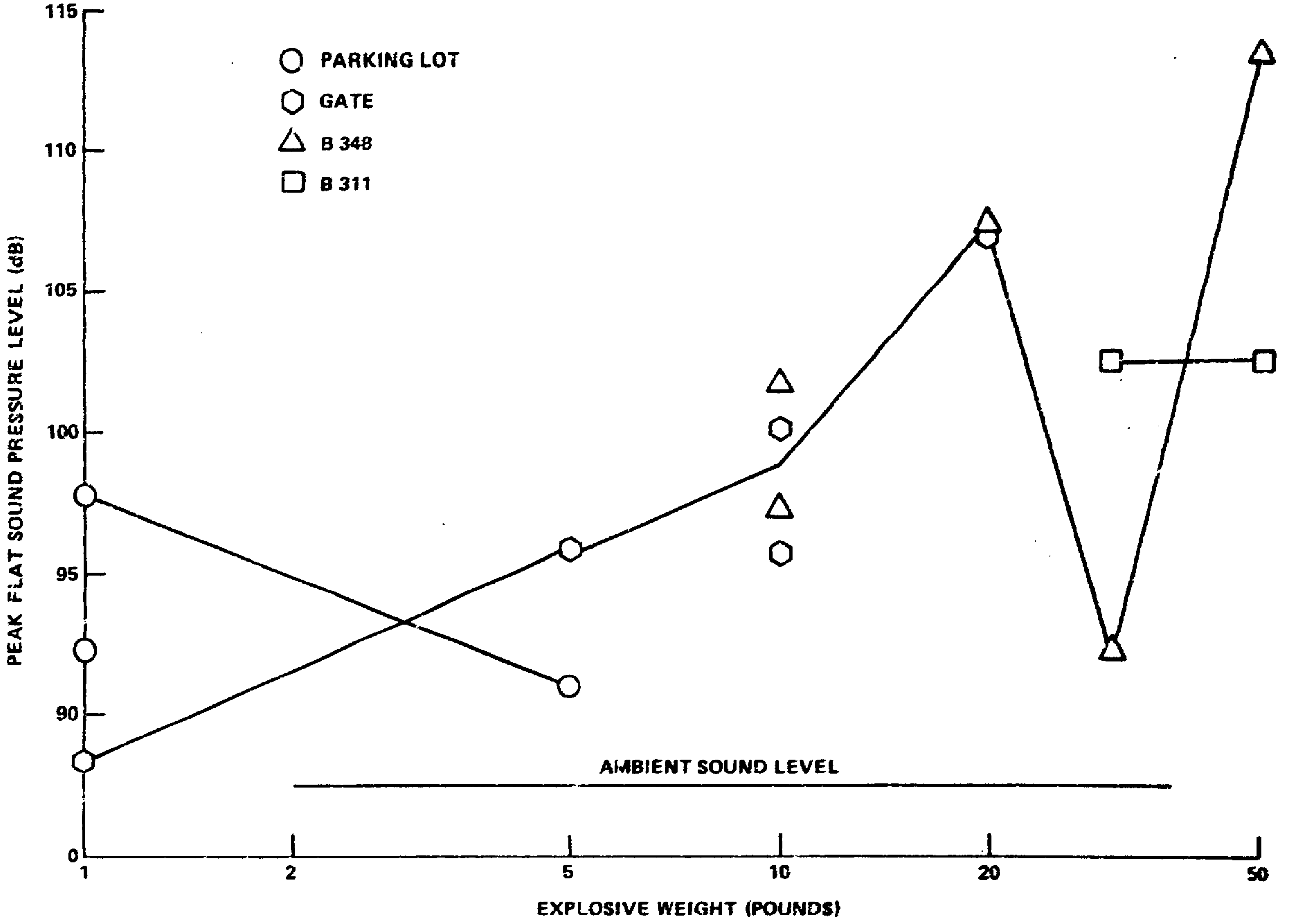


FIGURE 12. SOUND LEVEL VERSUS EXPLOSIVE WEIGHT OUTSIDE BUILDING 327

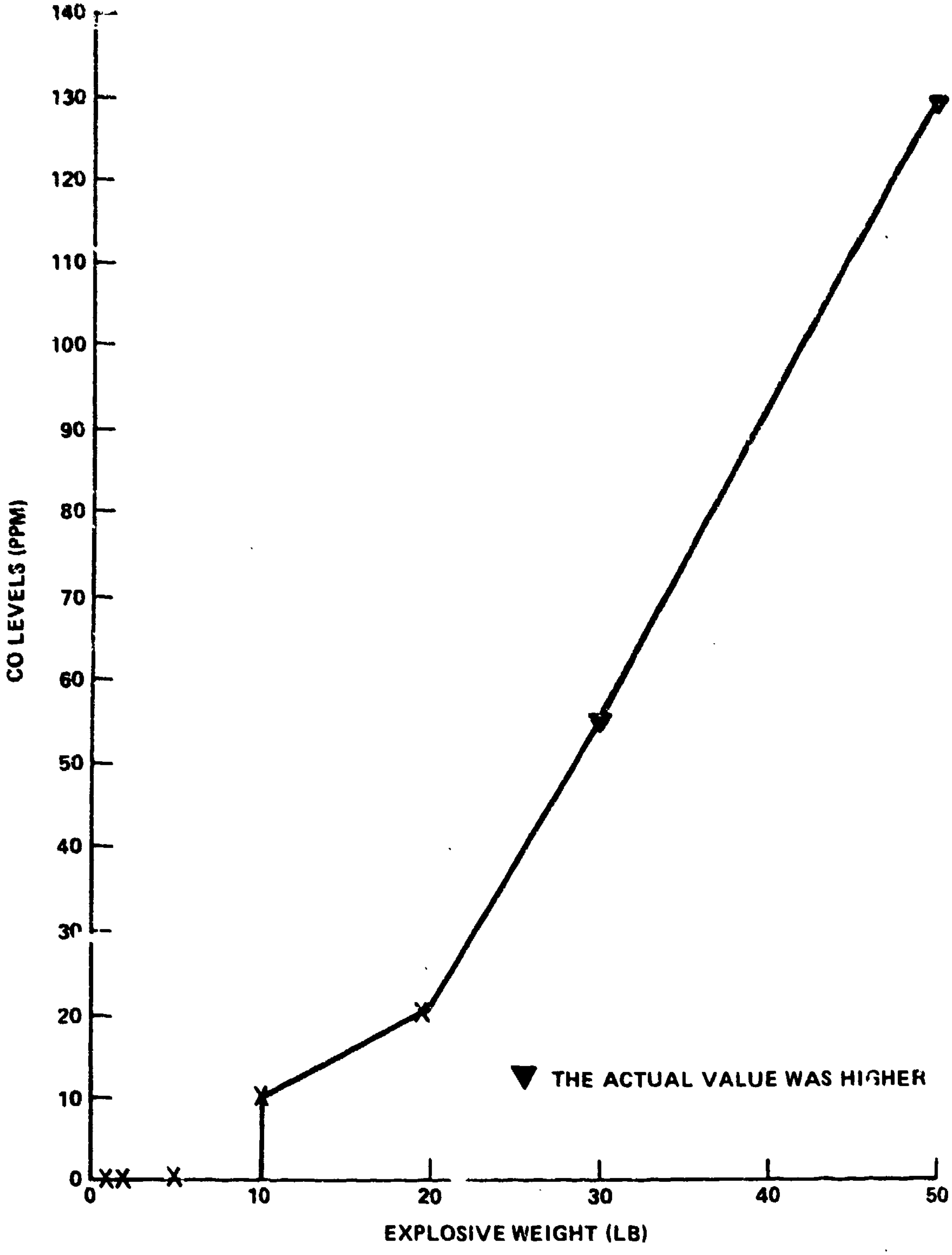


FIGURE 13. CO LEVELS RECORDED IN WORK ROOM

22nd Explosives Safety Seminar
26-28 August 1986, Anaheim, California (USA)

Design of a closed test facility for terminal ballistics

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1. Introduction

For the furtherance of the research at the Prins Maurits Laboratory on both internal and terminal ballistics a fully closed test facility has been designed. This facility will afford an opportunity for the dynamic testing of shells and for firing projectiles on explosive targets, while also static detonation trials are possible. Performing tests like these in the open air causes a lot of trouble, especially in a crowded country like the Netherlands, with respect to safety distances and noise pollution. Fundamental research on ballistics requires accurate measuring which is hardly possible in the open air.

The facility will, basically, consist of a gunroom and a target room, interconnected by a tunnel. Measuring rooms have been projected alsongside the gun and target room and also on top of the target room. From these rooms it will be possible to observe and study the experiments with the help of high-speed and X-ray photography. For that purpose a few closable windows are needed in the walls and roof. The major problem in the design was the lay-out of the target room. This room should be able to withstand a very severe explosion and impact loading, while on the other hand film-windows were needed at a rather short distance from the explosion point as well as a large door to allow the passage of target plate arrays:

This problem was solved by adopting a rather unusual shape for this building, which will be discussed now.

Although many details had to be solved for the constitution of a closed test facility in this paper only some attention will be given to the determination of the internal loading and the anchoring system of the wall-cladding.

2. Requirements

The main requirements that did affect the final design of the facility were:

- The target room must withstand an unlimited number of explosions of 25 kg of TNT equivalent without any damage.
- If a projectile of 35 mm hardcore accidentally misses the target it may not perforate the wall of the target room.
- Guns with calibres up to 76 mm will be used in the gun room.
- The entrance to both target and gun room has to be at least 3 x 2,5 m^2.
- During a test the facility should be fully closed.
- After an experiment the facility has to be vented very rapidly, so that it can be entered after about 5 minutes.
- Much attention has to be given to safety. So, for instance, special precautions are required to ensure that every door is locked before an experiment can be executed.
- No nuisance should be caused to the surroundings. Therefore special attention has to be given to noise pollution.

3. Lay out of the target room

Most structures designed for explosive loadings are very rigid. More recently, however, there is a tendency to make these structures flexible, in order ot absorb a lot of energy by (plastic) deformation. This can be illustrated with the help of a one-mass-spring-system, loaded by an impulse i. The kinetic energy transferred to the structure is:

$$E_k = i^2/2m$$

This has to be converted into the deformation energy E_d, which equals the area under the load deflection curve of the system. So for elastic behaviour:

$$E_d = {}^1/2\ q\ .\ x$$

and for plastic behaviour:

$$E_d = q \cdot x$$

where q is the maximum resistance and x the maximum deformation of the system.

Therefore it yields:

$$i^2 = m.q.x \text{ (elastic) or } 2.m.q.x. \text{ (plastic).}$$

From these equations it is clear that, for a given loading, the strength that is needed can be reduced by increasing the mass and/or the deformation capacity of a structure.

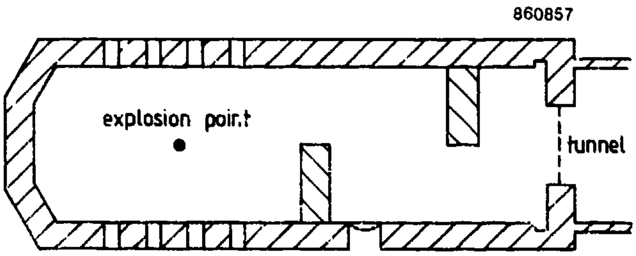
The loading is determined by the amount of high explosive and the inner dimensions of the target room. The desired distance between experiment and wall is more or less fixed at a value which is a compromise between the need for enough room for big targets on the one hand an the wish to make accurate photographs from the measuring rooms on the other. As the design load has to be withstood many times, plastic deformations of course are unacceptable. However, also the elastic deformations have to be small as they do influence the accuracy of the measurements.

The desired strength of the structure can therefore only be reduced by increasing the mass of the structure. This is also favorable for the reduction of the noise and for fulfilling the demand that a projectile may not perforate the wall.

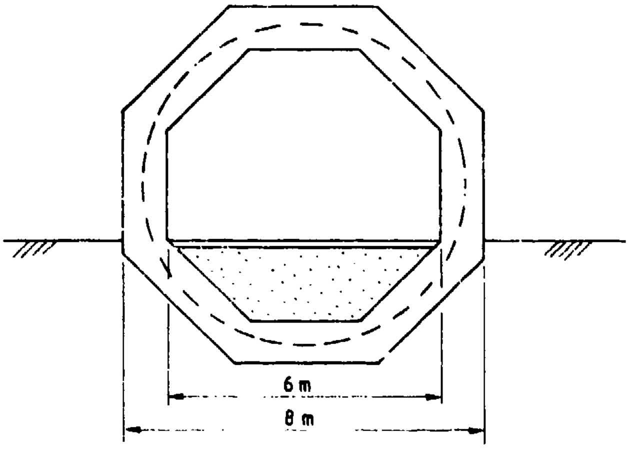
So a very rigid and heavy structure is needed. The rigidity of a structure is not only influenced by its dimensions but also by its shape. The rigidity is highest if the shape is chosen such that no bending occurs but only pure tension or compression. For a structure that is loaded internally therefore the optimal shape is a cylinder or a sphere. Too meet the strength and stiffness requirements a rather thin steel wall might be sufficient, but this does not have enough mass. Therefore it is preferable to use heavy walls of, for instance, reinforced concrete. Hence, the ideal solution is a thick-walled cylinder or sphere of reinforced concrete. The explosion point then should be in the centre of the sphere or somewhere on the axis of the cylinder.

After the decision was made to opt for a spherical or cylindrical room the major problem was where to position the entrance. A big hole somewhere in the spherical or cylindrical wall would disturb the force distribution in an unacceptable way. Besides, in a spherical room the door would be very near the explosion point and therefore be submitted to an enormous loading. The best way is to position the door in one of the end-caps of a relatively long cylinder. The cylinder then has to be in a horizontal position.

Since a structure with curved walls and floor is far from ideal to work in the circular cross-section was approximated by an octagon. The final plan is shown in Figure 1a, with a cross-section in Figure 1b.



Longitudinal section target room



cross-section target room

Figure 1: Shape of the target room

The wall thickness of the octagon is 1 m. This thickness in relation to the diameter makes it possible to draw a circle which is invariably in the central third part of the octagonal wall, cf Figure 1b. The reinforcement will also be given a circular shape. Therefore it may be assumed that the octagon will behave almost like a cylinder.

This assumption was checked with a finite-element calculation (paragraph 5). As can also be seen in Figure 1b the bottom part of the octagon will be filled with sand covered by loose plates. This has the advantage that the remaining room is much more convenient to work in. Another advantage is that the floor can readily be required if it is damaged: the plates can be replaced. A disadvantage, of course, is that this disturbs the uniform loading on the walls.

As to the plan: Figure 1a shows the entrance relative to the explosion point. It leads into the tunnel which interconnects target and gun room. In the side-wall of the tunnel there is the main entrance.

There are two transverse walls thougt in the target room that have to protect the entrance door against both direct shock wave impingement and fragments.

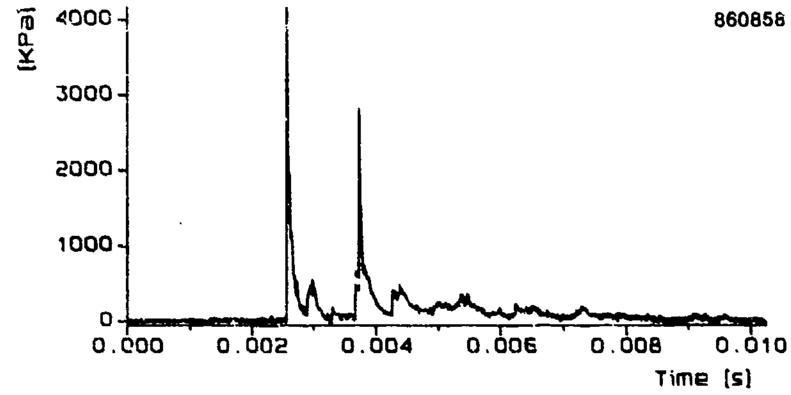
In the wall near the explosion point there are a few small windows: about 0,5 m square, which can be covered on the inside with steel plates. Just behind the first transverse wall a small door for the entrance of personnel has been projected.

4. Determination of internal blast load

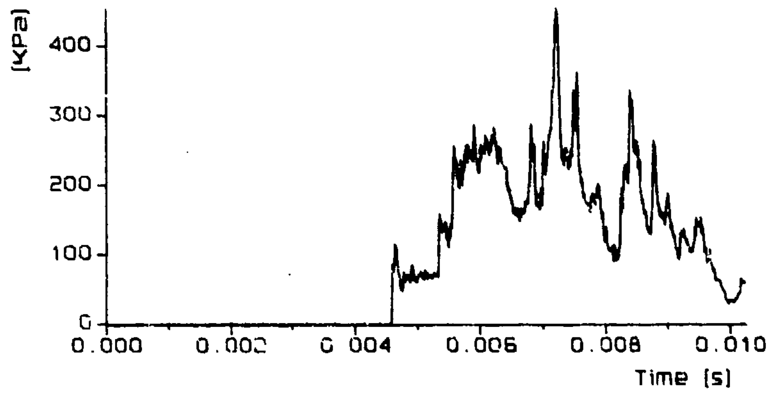
The first shock wave that hits the wall nearest to the explosion point can be calculated with the help of the literature by assuming a free air explosion at this distance.

The repeated loading here, as a consequence of multiple reflections, can only be estimated from the literature. The loading on the transverse walls and especially behind these walls and near the entrance cannot possibly be predicted. Therefore it was decided to do some tests in a scaled model. For the sake of simplicity a steel cylinder was used instead of an concrete octagon. In this cylinder an amount of sand was brought and covered with tiles to simulate the loose floor plates. Thick steel plates were welded inside the cylinder to simulate the transverse walls. As a scaling parameter the square root of the ratio in cross-sectional area was used, which resulted in a factor of 6.2.

In this model a few tests were performed. Some results are given in Figure 2.



a on the wall, near the explosion point



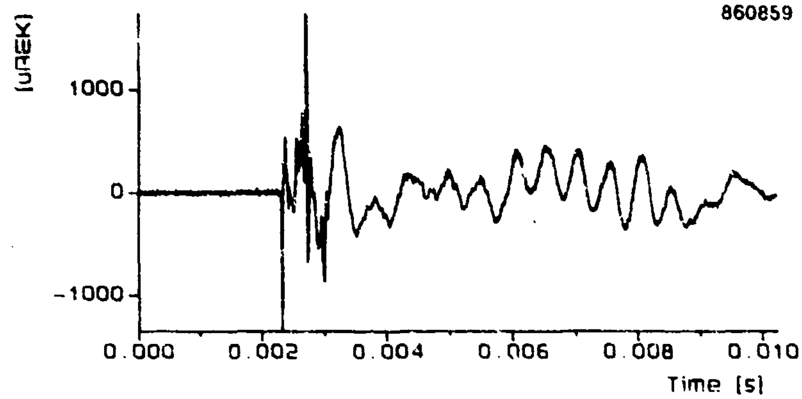
b near the entrance

Figure 2: Overpressure-time relations measured in the scaled model

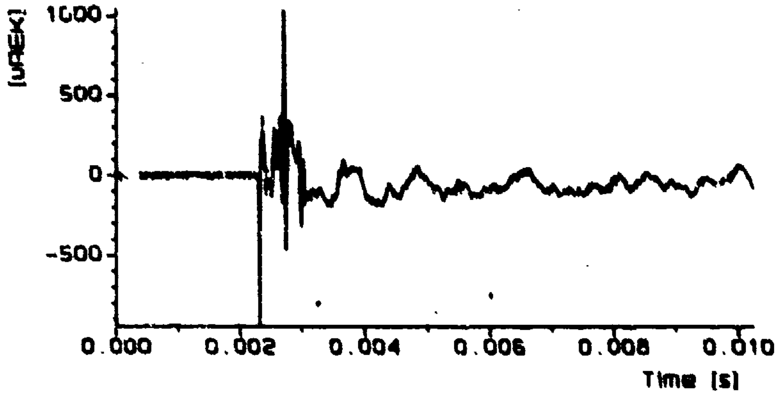
Figure 1a shows the overpressure as measured on the wall very near the explosion point. Two strong shock waves can be distinguished. The overpressure in the first one corresponds to the reflected overpressure in a free-air burst at this distance. The time between the two waves is 1.2 ms. In this time interval the shcok wave will travel about 1m. Therefore the second shock wave must be the reflected shock wave from the opposite wall. Figure 2b shows the overpressure as measured near the entrance. It is clear that the transverse walls reduce the overpressure considerably. Besides the shock wave loading also the static overpressure that will result after the damping out of the shock waves has to be taken into account. This static overpressure only depends on the loading density and will be here about 0.3 MPa.

Because of the great difference in magnitude between the shock waves and this static loading it is very difficult to measure them both with the same transducer in the same test. Since there is no reason to doubt the static values as they are given in literature no attempt has been made to determine the static overpressure experimentally.

In the model tests also strain measurements were performed on the cylindrical wall. Some typical results are given in Figure 3.



a. above the sand



b. below the sand

Figure 3: Strains as a function of time measured on the steel cylinder

The first short peaks are electromagnetic pulses from the explosion that are received by the strain gauge which serves as an antenna. This is proven by the time base: the peaks start before the shock wave reaches the wall as can be seen when comparing Figures 2a and 3. As an extra check an additional strain gauge was used which was not cemented to the cylinder and therefore should not measure any strain. With this gauge the same typical peaks were measured. The strain measurements can be used to gain an impression of the influence of the tiles-on-sand filling on the ideal cylindrical behaviour. The period of the vibration corresponding to this ideal behaviour can be calculated to be 0.6 ms. It is clear, especially from Figure 3a, that this vibration dominates the response. In Figure 3b the vibration shows considerable damping. Therefore the main influence of the filling on the response of the structure was the damping of the vibrations. The filling did not introduce much bending in the cylinder. As the steel model is much more slender than the real structure this last conclusion will hold even more for the real structure.

5. Finite-element calculations

The response of a cylinder under an equally distributed dynamic loading can be calculated very easily because the structure may be simplified into a one-mass-spring system. In order to gain more insight into the behaviour of the real octagonal structure some calculations were made with the finite-element code ABAQUS. As an example the results are shown for the structure under an equally distributed impulse loading.

For reasons of symmetry only one sixteenth of the structure has to be calculated, see Figure 4.

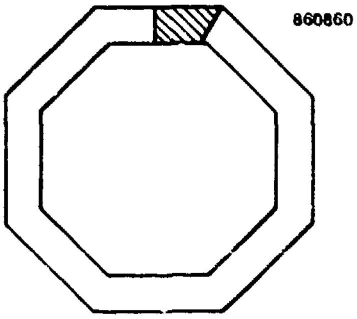
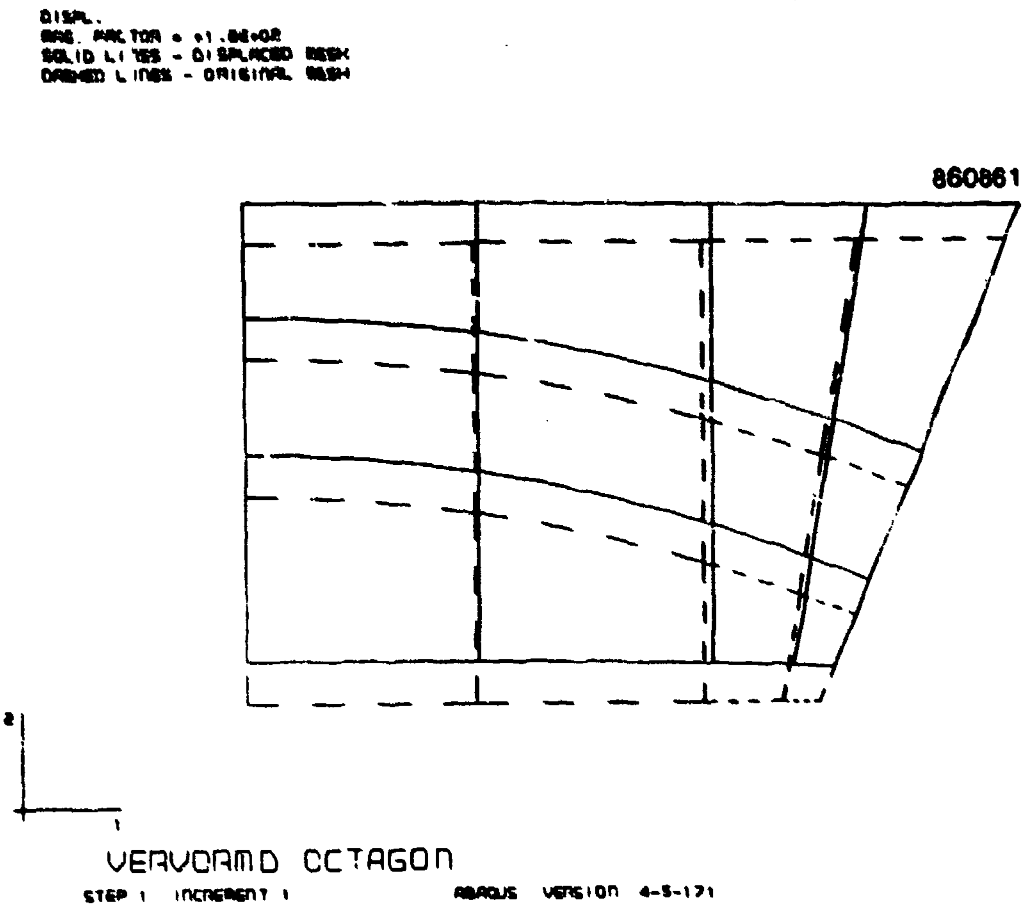
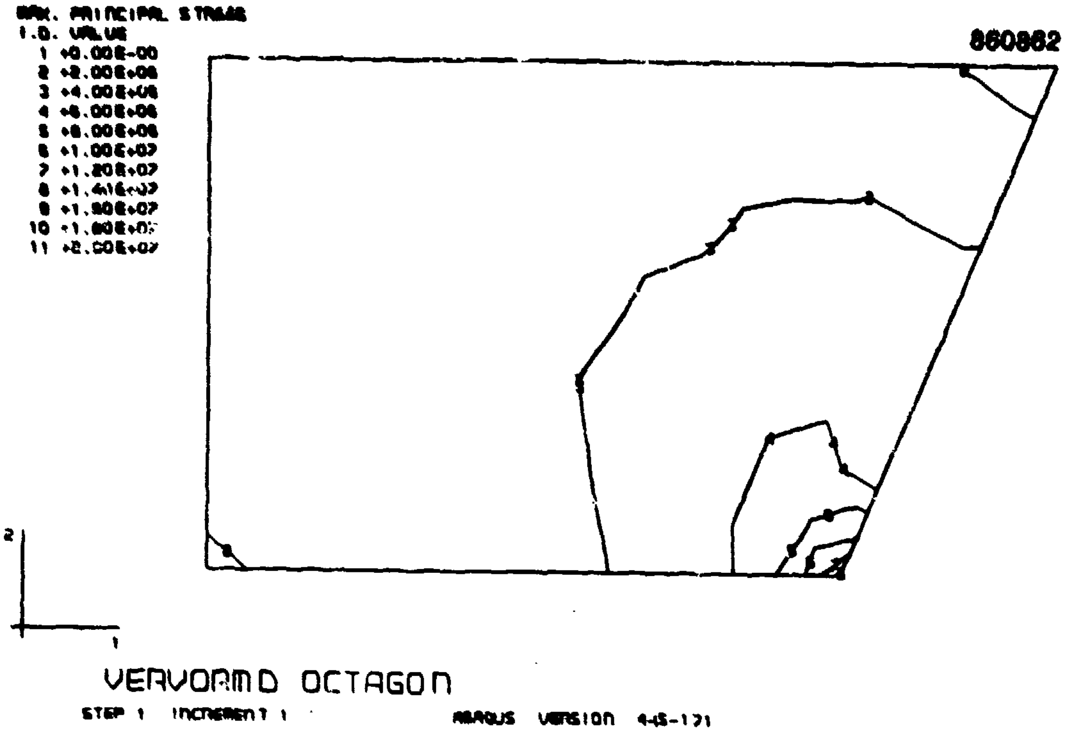


Figure 4: Part of the structure to be calculated

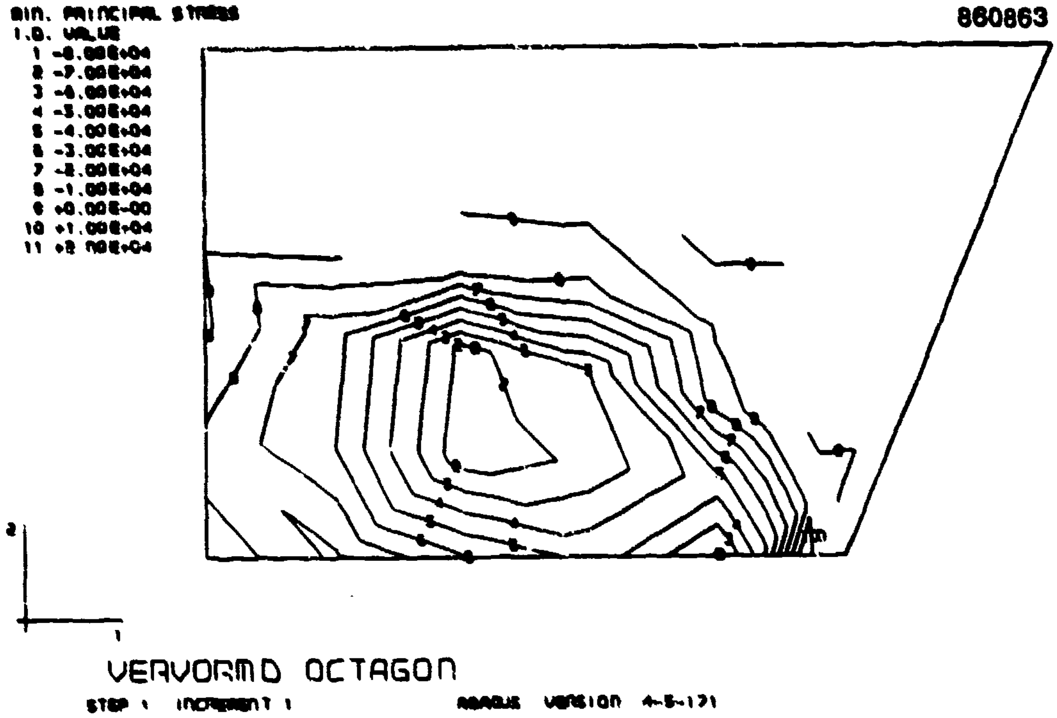
The impulse loading is taken into account as an initial velocity. The material behaviour, for this calculation was linear elastic. Results are given in Figure 5a for the displacements and in 5b and 5c as contour plots of the principal strasses.



a. Plot of the displacements



b. Contour plot of maximum principal stresses, in Pa



c. Contour plot of minimum principal stresses, in Pa

Figure 5: Results of a response calculation with
finite elements

The minimum principal stresses are of the order of about one percent of the maximum principal stresses and therefore neglegible. From Figure 5b it is clear that the maximum stress is more or less constant in most of the elements. As can be expected deviations occur near the corners. Especially in the right-hand bottom corner there is considerable stress concentration.

6. Wall-cladding

In most of the existing facilities for tests with high explosives the walls are covered with steel plates. Normally these plates are not in direct contact with the (concrete) walls: between the plates and the walls often wood is applied, either concentrated in a number of beams or distributed over the entire wall. Instead of wood also rubber is applied sometimes.

A major problem is always the connection of the steel plates with the wall. After a number of experiments often the anchor bolts gradually begin to loosen. Here, for the target room also steel cladding is considered. The problem of preventing the anchor bolts from loosening was tackled by studying the origin of the high forces on the bolts and searching for means to reduce them. The cladding was simplified to a one-mass-spring system. Its mass consists mainly of the steel plate, together with some of the backfilling material. The spring stiffness under compression is the stiffness of the backfilling, together with the bending stiffness of the steel plate if it is not supported uniformly. Under tensile loading the stiffness is only caused by the anchor bolts. This is schematically drawn in Figure 6.

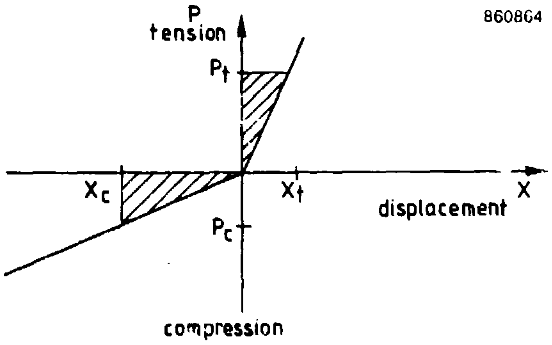


Figure 6: Spring characteristic for wall cladding

In general, therefore, the stiffnesses are different for tensile and compressive loadings. If the system is loaded by a shock wave the backfilling material is compressed. This is indicated in Figure 6 by a displacement x_c, corresponding to a pressure p_c. The amount of deformation energy in the system equals $^1/2.x_c.p_c$: the shaded area. Because the loading is dynamic the system starts to vibrate. This may lead to tension in the system. The tension is maximal when the loading is impulsive. Then all the energy absorbed during the compression phase will be set free and has to be absorbed again in tension. This is indicated in the Figure by p_t and x_t. The deformation energy now equals $^1/2.x_t.p_t$.

As the amounts of energy have to be the same this results in:

$$x_c \cdot p_c = x_t \cdot p_t$$

With this expression the problems with the anchor bolts can be explained. If, as a backfilling, wooden beams are used the displacement x_c is at least several millimetres. In order to prevent the loosening of the bolts often very strong and stiff bolts are used. Therefore x_t is very small. This will lead to an enormous tensile loading p_t on the anchoring system, which can be much more than the loading p_c with which the steel plates were compressed against the wall.

It is therefore much better to reduce the flexibility of the backfilling system and to make the bolts as flexible as possible. The most rigid structure is a direct contact between steel plate and concrete walls. However, this could cause damage to the concrete if the steel plate were hit by a fragment. Therefore a rather thin backfilling of plywood was chosen. The necessary flexibility of the bolts will be reached by using very long bolts that are screwed into sockets cast deep into the concrete. Another possibility is the use of spring washers, but with the calculation method outlined before it could be proven that this was not necessary.

7. Conclusions

For the furtherance of the research at the Prins Maurits Laboratory-TNO on both internal and terminal ballistics a fully closed test facility has been designed. On the basis of various requirements it is shown that the optimal shape for the test facility is a thick-walled cylinder of reinforced concrete. However, for practical reasons, an octagonal cross-section has been selected for the final design of the test facility.

The design study was supported by the results of experiments with a scaled model to estimate the internal loading on the walls of the target room. Further finite-element calculations have been carried out to determine the dynamic response of the structure.

SAFETY IN ORDNANCE TESTING

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Aerojet Ordnance Company develops and manufactures medium caliber ammunition and air-dispensed munitions. To support the development and manufacturing efforts, the company is heavily involved in ordnance testing. Although many of the safety problems associated with ordnance testing are similar to those found elsewhere in the defense industry, there are also unique safety considerations.

In the past, almost all of the safety analyses performed on ordnance systems have focused on either the ordnance device or the manufacturing facility. While these analyses are certainly necessary, a third important area requiring at least as rigorous an analytical effort is frequently given less-than-adequate attention. This is the ordnance test program, which usually consists of the following efforts:

Development Testing. These tests are conducted to demonstrate concept feasibility, verify compliance with performance requirements, and define performance characteristics. Such tests normally occur during the engineering development phase of the system life cycle.

Acceptance Testing. These tests are conducted to verify the ordnance system is ready for production (preproduction or first article acceptance testing), or that manufactured hardware is acceptable for delivery to the government (lot acceptance testing). Such tests normally occur at the start of and during the production phase of the system life cycle.

Long-Term Storage Surveillance Testing. These tests are conducted at regular intervals to verify that hardware has not deteriorated during storage. For example, the firing circuits of rocket motors stored in government inventories are typically tested every one or two years. There is a trend to warrant conventional munitions systems, which will require live testing of ordnance systems pulled from long-term storage facilities. Such tests will normally occur during the storage phase of the system life cycle.

Operational Testing. These tests validate the entire ordnance system (including procedures, delivery conditions, and hardware) using operational personnel and equipment. The Initial Operational Test and Evaluation (IOT&E) is a test that validates the design prior to production. Follow-on Operational Testing and Evaluation (FOT&E) is a test that validates the procedures and hardware prior to deployment.

As can be seen from the above, there is a significant level of activity associated with testing ordnance systems. In fact, most conventional ordnance systems see more use in the test environment than in any other. Due to the fact that unsafe test hardware, fixturing, procedures, or location can have disastrous consequences, application of rigorous system safety engineering techniques to all activities associated with ordnance testing is essential.

Hardware Safety Analysis

In an ordnance test environment, one must be concerned with the safety of the item being tested, the test fixturing, and hardware used to dispose of the test item. In most cases, the ordnance device is extensively analyzed as a normal part of the system safety program (preliminary hazard analysis, failure modes and effects analysis, fault tree analysis, etc.).

Safety analysis of test fixturing (including instrumentation) is equally important, yet it seldom receives the same depth of analysis. The analyses prepared for the ordnance device should be used as a starting point to familiarize the engineer with the conditions required for arming and detonation, and how the device might behave under unusual conditions. Once this is done, the same types of analyses prepared for the ordnance device should be prepared for the test fixturing. Fault tree analysis, in particular, is strongly recommended to identify the required conditions and probability of occurrence for such events as inadvertent arming or detonation, failure to function, loss of control of the ordnance device, and explosive residue.

The fixturing (or lack of fixturing) used to recover and dispose of any explosive residue is another critical hardware analysis area. The explosive residue could be as small as a detonator, or as significant as a dud submunition from a cluster bomb unit (see Figure 1). Since personnel are normally involved in the disposal of explosive residue, the equipment used for this purpose should be included in the safety analysis.

While pursuing traditional hazard identification methods (location of all energy sources, consequences of improper assembly, out-of-sequence operator actions, etc.), the analyst should review the history of similar weapon systems. Although the state-of-the-art in ordnance system and test fixture design is continually evolving, many of the likely hazards have been experienced on earlier systems. A review of this failure history will provide valuable design guidance for both the ordnance system and the test fixturing.

Design reviews should be held for the test fixturing just as they are for the test item. Senior members of the technical staff as well as qualified system safety engineers should participate in the review. The temptation to assess the safety of test fixturing based solely on the opinion of the test engineer or technician must be resisted. A recent quote in Hazard Prevention best explains the reason for this: "... repeated uneventful experience with a hazard may reduce disproportionately its perceived risk ..."[1]

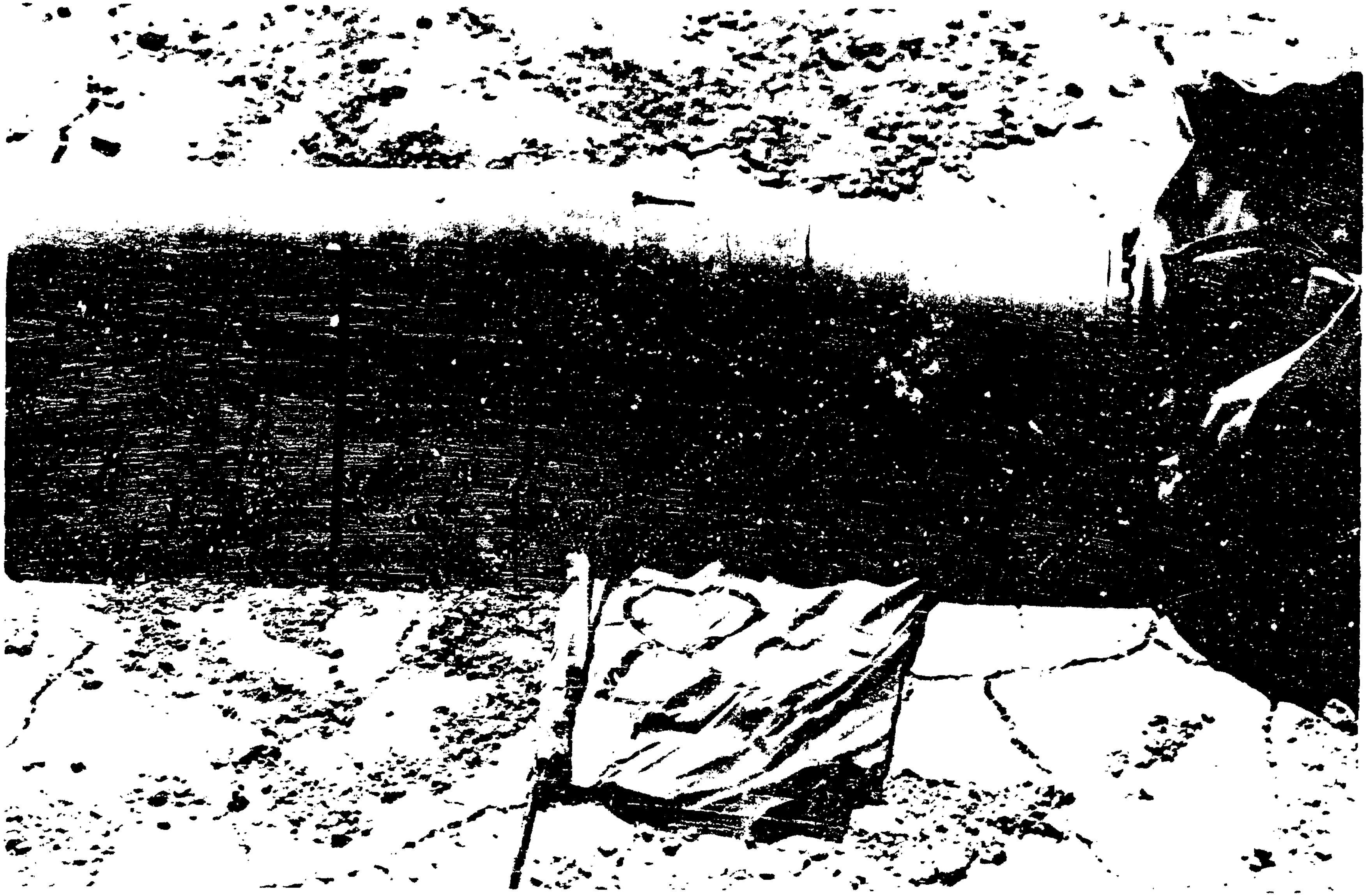

Figure 1. Example of test residue. Armed live BLU-97/B bomblet from a recent CBU-87/B flight test.

Ordnance test engineers and technicians frequently develop a disregard for the severity of a hazard for this exact reason. Further, relying solely on the judgement of those required to perform the test places these people in an awkward position. Ordnance test personnel may feel that their capabilities or dedication to the job will be compromised if they question the safety of a test.

Depending on the complexity of the test fixturing, the fixturing design review can sometimes be combined with the test review. The test review will be described in the next section.

Procedural Safety Analysis

An operating and support hazard analysis (O&SHA) of the test procedure is critically important to the conduct of a safe test. The O&SHA should draw upon all of the safety analyses described above, as well as the test procedure. The O&SHA should include a time line analysis and a walk-through of the test procedure to determine if the required steps can be safely accomplished within the ordnance device's timing constraints. During the walk-through, all required protective equipment (face shield, gloves, flak jacket, etc.) should be worn to identify any human factors considerations that might not otherwise surface. On one such recent test, a walk-through identified a hazard that was adequately controlled through a procedural change (see Figure 2).

This example concerns the Combined Effects Munition System, which, Aerojet Ordnance Company is currently producing and testing for the U. S. Air Force. CBU-87/B Lot Acceptance Flight Testing is conducted at the Aerojet test facility at Hawthorne, Nevada, while Follow-on Operational Test and Evaluation is being conducted by the 57th Fighter Weapons Wing at Nellis Air Force Base, Nevada. Prior to Aerojet's actual conduct of the first full-up high-explosive drop, table top reviews, simulations, walk-through-talk-throughs, and one complete dry run using inert items were conducted to verify the test plan and the procedures that support the plan. An historical perspective on the Lot Acceptance Flight Test procedure was provided by discussion and observations of how the U. S. Air Force was conducting Follow-on Operational Test and Evaluation tests at Nellis Air Force Base, Nevada. Several areas of concern were identified and corrected. For example, the review found that the run-in line to the release point for the delivery aircraft went over a mountain which was 200 feet higher than the release altitude. The aircraft flight path was modified accordingly.

In addition to uncovering hazards inherent to the conduct of the test, the O&SHA should assess the clarity, adequacy, and accuracy of the test procedure. If the procedure is difficult to understand or must be worked around, it should be rewritten. The use of universal test procedures (i.e., those containing information designed to allow the test technician to perform any of several tests by turning to selected pages, or those written in general terms and intended to allow operator latitude) is strongly discouraged. The procedure should contain adequate warnings that are clearly visible and appear prior to the affected operation. The O&SHA should also check for and assess the steps to take in the event of any

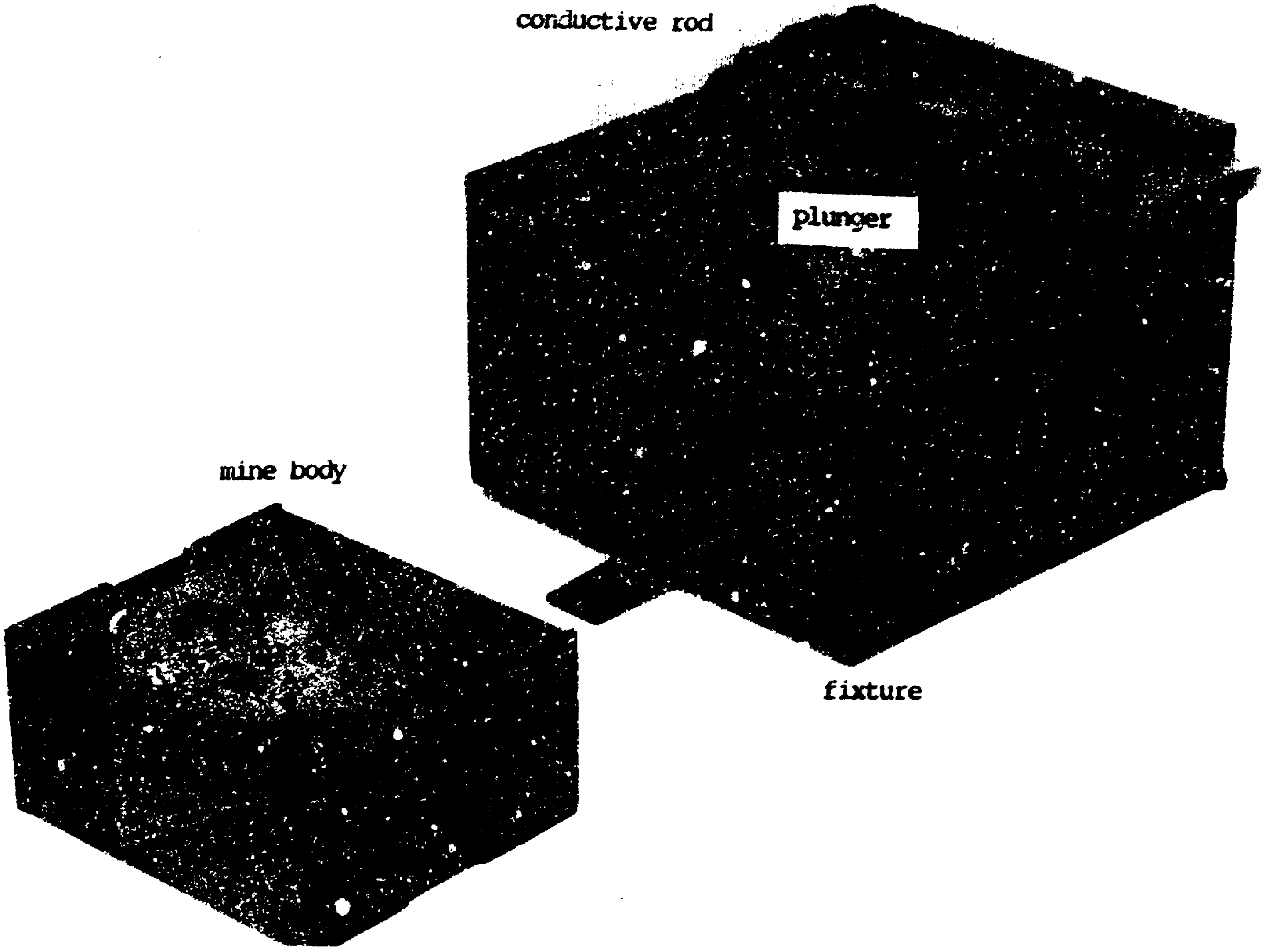

Figure 2. Test fixture used to record firing of the GATOR mine body assembly. When the mine body fires, it pushes the plunger on the top of the fixture upward, breaking a conductive rod. A walk-through of the procedure showed the need to perform all electrical connections prior to placing the mine in the fixture (if the mine fired early, the technician could be injured by the plunger).

unusual occurrances. Finally, the O&SHA should review existing procedural checklists, and recommend any other required checklists.

When preparing the O&SHA, the system safety engineer should be sensitized to the differences between development testing and acceptance/surveillance testing. In development testing, a very small number of specimens is usually tested. Just the opposite is true during first article, lot acceptance, or long-term surveillance testing. Hundreds of samples may be randomly selected. For such a test, required operator actions may easily (and surprisingly) number in the tens of thousands. Since human error rates generally range from 10^{-2} to 10^{-3}, it becomes obvious that special procedures, checklists, and training will be required to limit the number of operator errors. Figure 3 shows the human error rates experienced during acceptance testing of a recent production program. The results of hardware and procedural analyses should be documented as part of the safety review, and changes made to appropriate test plans and CDRL items wherever deficiencies are noted.

Once the above analyses have been completed, a test review should be held. The test review is similar to the design review in that it includes senior technical personnel who are not directly associated with the project. The test review should identify the test objectives, how the test will be performed, and all associated hazards. The test review committee members should agree on the safety of the test before it is performed.

Organizational Culture

The effects of the hardware and procedural analyses on safety is frequently a function of the quantity and seriousness of management emphasis placed on the subject, and the resulting organizational culture. As is the case in all industries where hazardous operations are performed, incorrect safety-related opinions are occasionally expressed. In the ordnance industry, these erroneous concepts generally take the form of the following four myths:

> Myth No. 1: "Accidents will always occur ... it's just a question of spreading out the time between them ..."

A statistician may argue that in a pure technical sense the above statement is correct. Unfortunately, this attitude has no place in the ordnance test environment. The goal should be to have zero accidents. With proper test fixturing, procedures, and personnel protection, such a goal is achievable.

> Myth No. 2: "You have to prove the test is dangerous before we'll cancel it ..."

Just the opposite is true. Proper analysis must be performed to verify that it is safe to proceed with the test, rather than simply proceeding blindly unless someone can show that an uncontrolled hazard exists.

> Myth No. 3: "You have to be willing to accept risk ..."

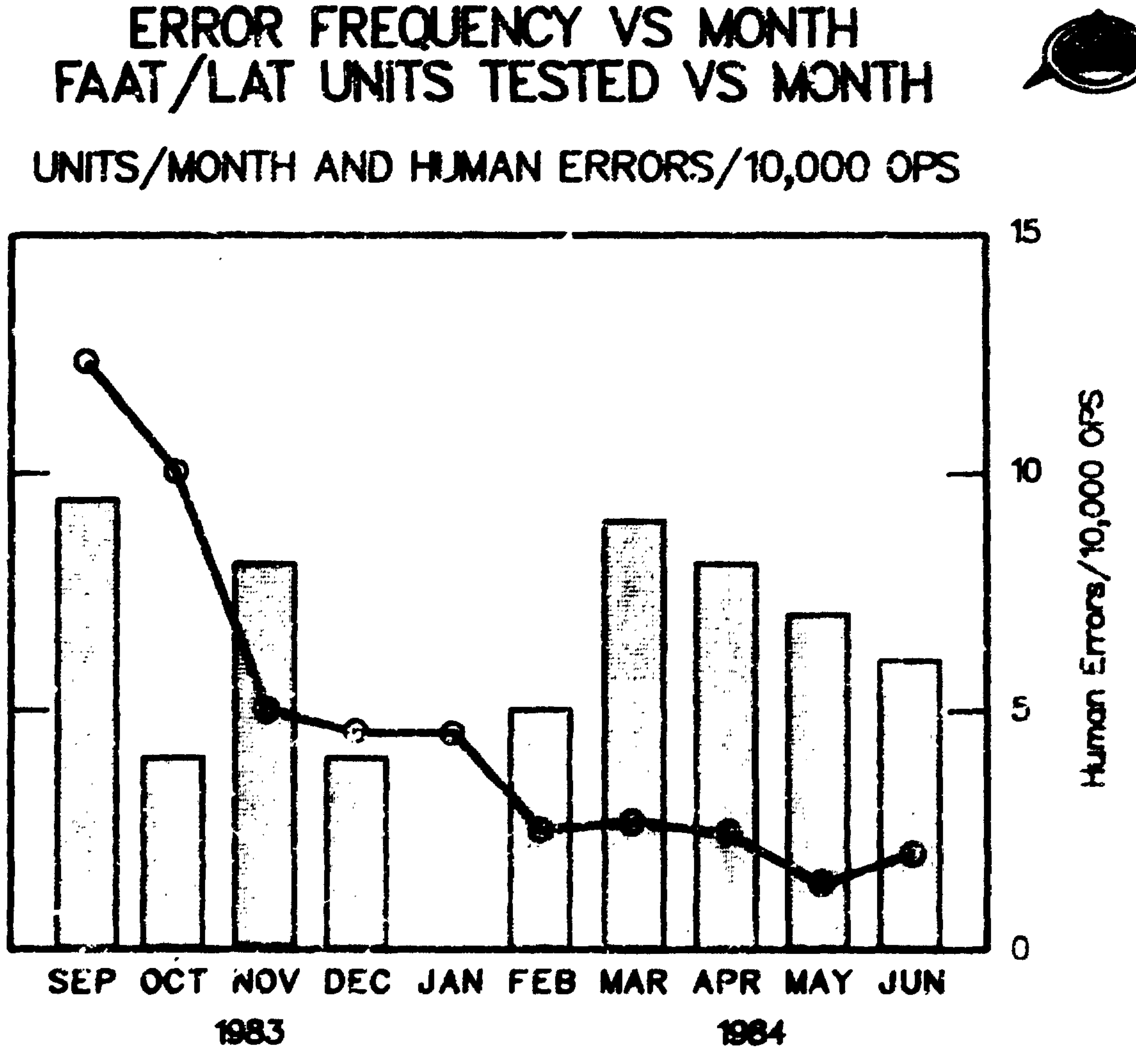

Figure 3. Human error rates experienced during a recent mine acceptance testing program. The bar chart shows the number of mines tested per month, while the solid line shows the cumulative error rate.

Accepting risk is a basic precept of doing business. However, unquantified risk (particularly when the consequence could be injury or death) must never be accepted.

> **Myth No. 4:** "If the ordnance test technician is willing to do it, then it must be safe ..."

For reasons explained earlier, ordnance test technicians and test engineers should not be the final authority to pass judgement on the safety of a test (unless they feel it is too dangerous to proceed). If these experts feel it is safe to proceed with a test, their opinions should be augmented with a sound system safety assessment.

Special Ordnance Considerations

Several safety-related peculiarities have been mentioned in the preceding paragraphs. Others that bear mention include test site location, crowd control, personal protective gear, adequate pre-explosive test and analysis, reduced explosive component testing, and electromagnetic interference/electrostatic discharge (EMI/ESD) protection.

Test Site Location

Test site location is critical to the safe conduct of any explosive testing to allow for proper test conduct, monitoring, and observation based on a prudent safety plan. An Operating and Support Hazard Analysis (O&SHA) should be conducted on the testing location to assure the test location will not prevent safe completion of the test. This analysis can draw upon or be part of the other safety analyses described earlier.

Crowd Control

Due to the often spectacular nature of an ordnance test, many people will want to attend. If spectators will be present, there should always be a designated spectator area located far enough away from the immediate test area to assure personnel safety under all conditions. Only those personnel necessary for the conduct of the test should be present in the immediate test area. Video camera coverage can allow those interested in the ordnance test to view its conduct. During acceptance testing of the GATOR mine body, for example, the mine was fired at high velocity into a particle board (see Figure 4). Even though no high explosives were present, resultant sabot debris required keeping personnel at a safe distance.

Personal Protective Gear

If it is necessary to handle an armed ordnance device during the conduct of a test, protective gear should provide adequate protection (based on the assumption the ordnance device will fire while being handled). This is true for small detonators only, and not for high explosive charges. If

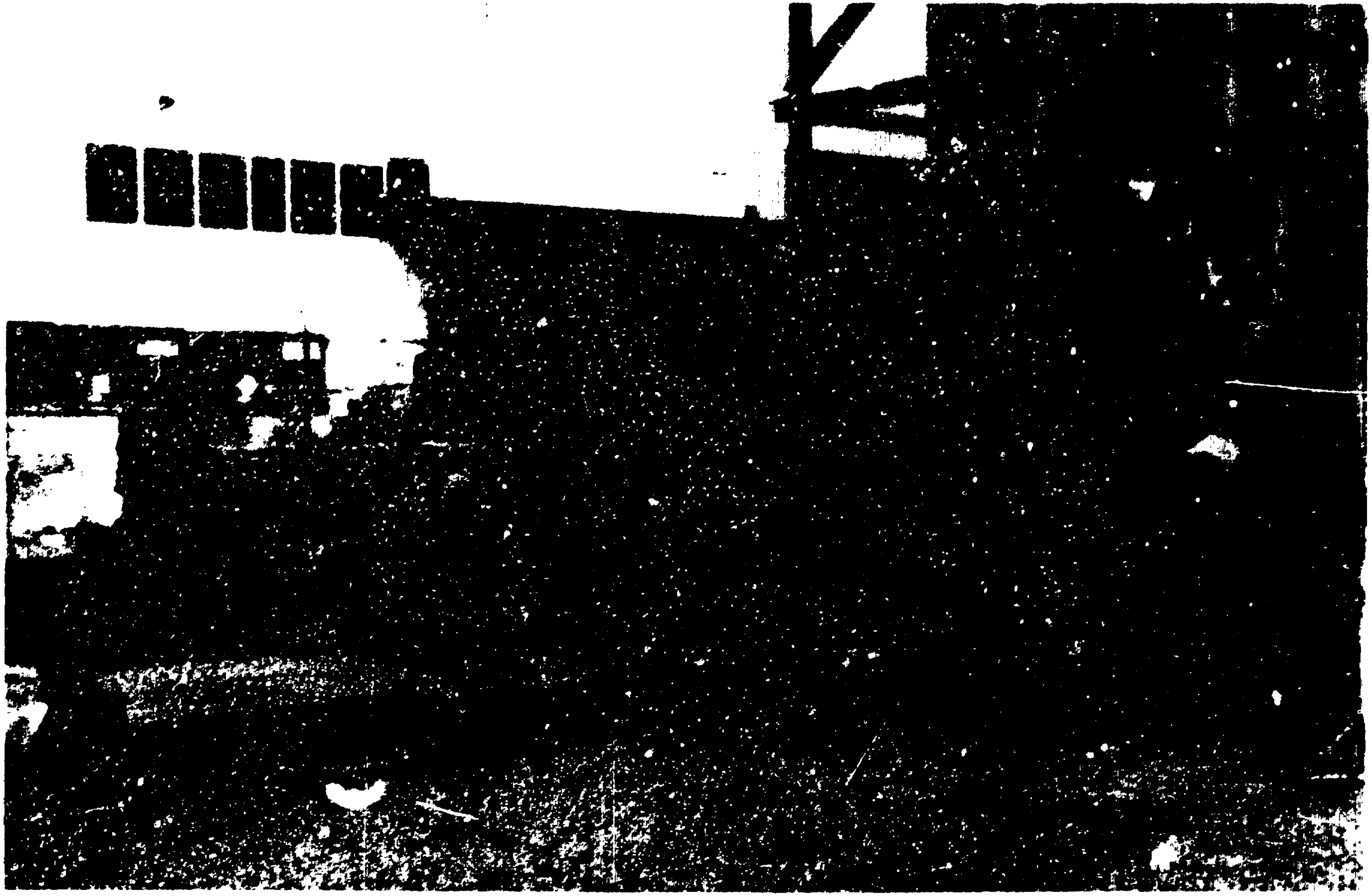

Figure 4. Acceptance testing of the GATOR mine body assembly. When the mine body is fired into particle board at high speed, the resulting debris from the mine sabot can be hazardous. The need for limiting access to this area is obvious.

protective gear will not provide adequate protection in the event of a detonation, the test must be done remotely.

Whenever possible, all test items should be handled remotely. During development efforts (where only a few items are built), this is often not feasible. Routine acceptance testing, however, generally occurs often enough to justify remote handling equipment. On one cluster munition program, submunition fuzes are tested entirely by remote handling equipment (see Figure 5).

The use of robots in ordnance test applications should be considered. As robot technology continues to improve, remotely-controlled robots will be used in more applications, particularly in recovery and disposal of test residue. Most large metropolitan police departments own robots for disposal of explosive devices, and their experience is often applicable to the requirements discussed in this paper.

Pre-explosive Test and Analysis

Warheads mounted on flight platforms should not be flight-tested until the stability of the vehicle has been demonstrated. Also, trajectory analysis should be performed to verify range safety of the products of high explosive warheads. In particular, attention should be focused on the possible fields of fire for the carrot from a shaped-charge warhead, and the slug from a self-forging fragment warhead.

Reduced Explosive Component Testing

As a general rule, ordnance tests should be conducted with minimum explosive components. Adequate system performance information can usually be obtained without the use of the main high-explosive charges. This approach has the added advantage of eliminating special range requirements. If a failure does occur, the explosive ordnance disposal requirements are greatly simplified, and there is generally hardware left to analyze.

The hardware safety analysis for the test device should identify the explosive items that might remain after a test. Even reduced explosive component testing can leave an explosive hazard. During Follow-on Operational Test and Evaluation testing of the Combined Effects Munition System, BLU-97/B submunition explosive components are reduced to allow confirmation of function (the BLU-97/B submunition contains a full fuze but an inert bomb body is used with a foil disc to indicate proper function).

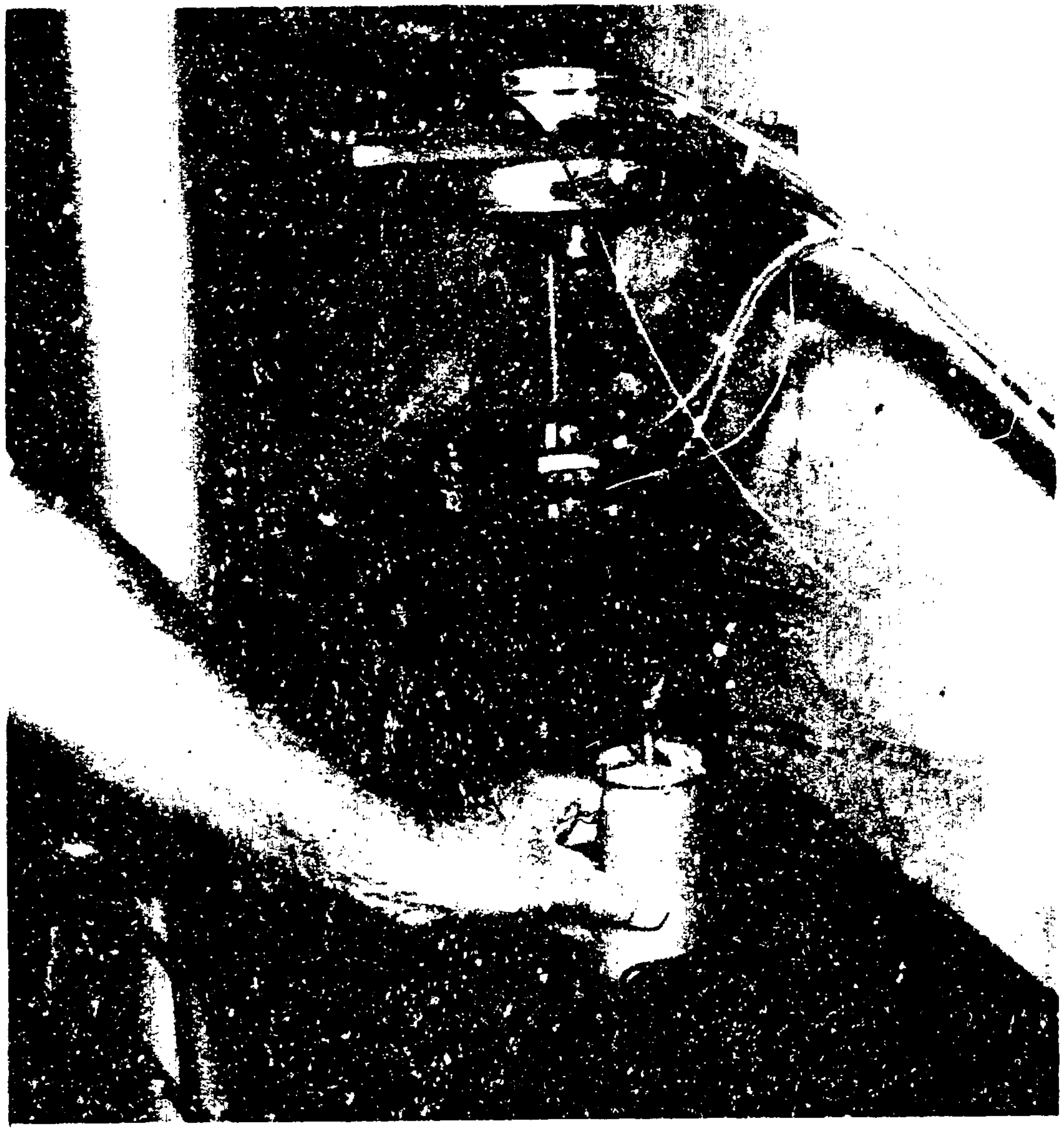

Figure 5. Pneumatically-operated test fixture for submunition fuze handling. All handling of the armed fuze is done remotely.

EMI/ESD Protection

Everything associated with an ordnance test should be grounded to help protect against electrostatic discharge. This includes fixturing, the ordnance device, and the technicians and engineers conducting the test. Many detonators are extremely sensitive to electrostatic discharge, and even when proper grounding procedures are followed, such devices will sometimes be energized by ESD. The system safety engineer must be aware of charges that can be generated in an area insulated from the ground plane. In one test, a plastic mine body contained a detonating device held in place by cellophane tape. Even though the technician and the mine were grounded, a charge sufficient to ignite the detonator resulted when the tape was peeled away from the mine body. The plastic mine body insulated the generated charge from the groundwires.

The effects of electromagnetic interference should also be considered, and protection provided accordingly. Test fixturing frequently contains long power or signal monitoring lines that can act as antennas. Such systems may be far more susceptible to EMI than the weapon being tested. The result may be an inadvertent command to the test item.

Summary

In the past, almost all of the system safety analyses done in the ordnance industry focused on operational deployment or manufacturing of the weapon system. Most ordnance systems see far greater use in the test environment, however, and greater safety emphasis is needed in this area. The analytical effort should focus not only on the item being tested, but also on test fixturing and procedures. An engineering process very similar to that used to verify the safety of the ordnance device should be used to verify the safety of the test fixturing and procedures. This should include classical system safety analysis techniques as well as independent senior technical design and procedural reviews. Special consideration should be given to the problems unique to ordnance testing.

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Captain David A. Mendoza has a BS degree in Mechanical Engineering from the University of Central Florida, and an MA degree in Management from Central Michigan University. He is currently the Chief Engineer on the Combined Effects Munitions System. Prior Air Force assignments include Chief of Facility Design in the Azores, and facility design engineering positions at Andrews Air Force Base, Maryland. Captain Mendoza has over eight years of experience in government facility and weapon systems acquisition engineering assignments.

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CRITERIA FOR BLAST DAMAGE FROM DISTANT GUN FIRE AND EXPLOSIONS

by

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Introduction

Activities on many Army installations involve the firing of guns and the detonation of explosives. These activities generate blast waves that propagate to neighboring communities and cause complaints of damage. This paper describes the procedure for processing claims, reviews the types of residential damage claimed, and describes the blast damage threshold criteria.

Cont
pg 6

The energy releases that disturb communities emanate from a variety of sources: muzzle blast from artillery and tank guns, blast from high explosive (HE) rounds fired by these weapons, and charges fired above, on and below the surface (see Figure 1). As one might expect, the large number of military reservations in the US with a potential for causing damage, resulted in the Army establishing a "regulation" to deal with complaints of damage. Army Regulation 27-20 was established and requires that claims of damage that cannot be settled by the offending government agency must be forwarded through the Staff Judge Advocate Office at Fort Meade, Maryland, to the Ballistic Research Laboratory at Aberdeen Proving Ground, Maryland, where they are to be evaluated and then returned to Fort Meade (see Figure 2) for final disposition and/or settlement. If the claim is denied the claimant has the right of appeal.

The claim file should contain statements by the claimant and reports by the offending agency. The claimant's report describes the nature of the damage incurred and the date of the occurrence. The spectrum of damage complaints is wide, ranging from cracked concrete to nail popping (see Figure 3). The agency alleged to have caused the damage prepares a report (with photos) that describes the condition of the structure and highlights any condition of the property that may have a bearing on the claim. In addition, the agency report includes a map which shows the position of the structure with respect to the explosion or gun firing point and a statement of details on the explosions or firing activities at the time of the alleged damage. If meteorological conditions at the time of the alleged damage are available, they are also included in the report.

Determining the blast pressure that a structure experiences as a result of these kinds of energy releases is often not a straightforward procedure. There are unknowns in the forcing function and unknowns regarding the response of the structure to a forcing function. In order to resolve the claim, assumptions have to be made that put the problem in a framework which allows drawing from an established database. Some of the assumptions are minor when considered in the light of the strong influence played by the atmosphere and the characteristic lack of information on the atmospheric conditions prevailing at the time of the blast. Figure 4 shows typical missing parameters.

Airblast, not ground shock, is the most important factor to consider in the claim evaluation process. Weak overpressures travel at near sound velocity and hence their propagation velocity with respect to the ground is significantly altered by temperatures and winds. For the charge weights and distances of interest, the travel time is relatively long and one can expect the atmosphere to have a strong influence on the pressure level. The missing elements in Figure 4 may well become unimportant because of the strong influence of the winds and temperature.

Static Charge and HE Shell

There are data relating pressure and distance for charges detonated on the surface and in free air, but no data in the very low pressure region (<1034 Pa or .05 psi), that can be used directly because of the strong influence of the changing atmosphere. A free air, pressure vs. distance relationship was established however, by a committee of the Acoustical Society of America [1]. It used a hydrocode to extend selected higher pressure data to the very low pressure region. The equation and curve, Figure 5, are taken from reference 1. This curve is used in claim evaluations to determine a baseline pressure which will be altered in some manner by the atmosphere. If the charge were detonated on the ground, the curve indicated by 2 kg would provide a better estimate of pressure in a standard atmosphere.

Chapter 5 of reference 1 contains a detailed description of the influence of real atmospheres in the low overpressure region and the author of the reference infers that pressure could be amplified by a factor of five under unusual meteorological conditions. If the claim file does not include pertinent meteorological data, the pressure obtained from Figure 5 is increased by a factor of five to ensure a fair evaluation. It is felt that the claimant should not be penalized because of a lack of specific information.

A claim which involves a structure that is close to a bare static charge allows the most accurate prediction of pressure. The atmosphere has had little time to influence the wave and there has been only a mild extrapolation of a rather extensive database. However, this case is rarely encountered because Army proving grounds normally fire static charges in remote areas. Accidental explosions could of course occur close to residential areas. The detonation of an in-flight HE shell is a frequent scenario for provoking claims of damage. For shell detonating in an impact area, one will not know the height of burst or have accurate positioning of the round. The lack of data on these variables is deemed not important for most cases because the distance between impact areas and residential structures is, by design, substantial. The procedure is to assume a free-air detonation on the near boundary of the impact area.

Muzzle Blast

Many claims stem from the muzzle blast of tank guns and artillery weapons. These produce a non-symmetrical blast pattern that extends from the near field to the far field. There is a directivity effect, an enhancement of the pressure in front of the weapon and attenuation toward the rear. The theoretical treatment of muzzle blast in the far field is shallow, but there are experimental databases. Schomer et al. [2] used pressure measurements from gun firings to relate pressure to available propellant energy, gun tube elevation and azimuth, and length of gun tube. Unfortunately, these parameters are not usually included in the claim file. Pater [3] conducted a study of blast from naval guns that was similar to the Schomer study. Both concluded that directivity can add as much as 14 db (a factor of five increase in pressure). Luz [4] used the Schomer pressure vs. distance data to determine the frequency of occurrence of disturbing pressures in communities that border tank gun and artillery firing ranges taking into account the range of meteorological conditions experienced in practice. Luz's work can be plotted to establish pressure vs. distance curves if a fixed frequency of occurrence is maintained. Figure 6 shows the pressures that could be expected to be exceeded by 1% and 50% of the firings in the direction of fire of a 120 mm tank gun. The difference in pressure between the 1% and 50% curves is attributed to changes in meteorological conditions. The plotting parameter db is related to Pascals, Pa, by the equation $\text{db} = 20 \log \frac{\text{Pa}}{20\text{x}10^{-6}}$. The data from the 120 mm sabot (KE) round was selected as a baseline for scaling because it would minimize the chance of having a significant bow shock signature, and the cartridge contains a significant propellant load. It should produce a maximum muzzle blast for its caliber. Figure 7 is a plot of pressures expected for 1% exceedance of the firings in the front, side and rear of the gun. The pressure differences are not as great as those attributed to meteorology and shown in Figure 6, but angle of fire can be important.

Figure 8 is an estimate of pressure for 1% exceedance from 155 mm howitzer firings. The projection was obtained by increasing the distance for selected pressures by the ratio of diameters of the 120 mm and 155 mm guns. The graph shows exceedance toward the front, side and rear of the weapon. The rate of pressure decay for all orientations is the same. Figure 9 is a similar plot for the 8" howitzer. The projections may overpredict toward the front of the weapons and underpredict toward the rear because of the presence of muzzle brakes on many artillery weapons. Artillery firing positions are often near the military reservation boundary, allowing the weapon to fire to a rather centrally positioned impact area. The figures show that rather high pressures can be experienced within 5 km of large caliber guns when meteorological conditions are unfavorable.

Criteria based on 1% exceedance do not account for the "unusual" day. In other words, what actual maximum pressure could be expected when the value at 1% is exceeded. Recent firings at Aberdeen Proving Ground afforded an opportunity to obtain a rather unusual set of data that included what is considered to be a maximum pressure. A 155 mm howitzer fired 100 inert rounds on a day when no other guns were firing. This allowed one to associate the pressure measured at a recording station with a specific gun at a specific location. The propelling charge and angle of elevation of the howitzer were such that the projectiles traveled supersonically from the muzzle to apogee. They did not exceed the speed of sound on their downward trajectory. The scenario indicates that the pressure measured was from muzzle blast and not the ballistic wave. Unusually high readings were obtained at one monitoring station which was down range of the weapon and 39 degrees off of the line of fire. A plot of sound velocity as a function of altitude in the direction of the station within a few minutes of the high reading is shown in Figure 10a. The plot includes the added velocity due to the component of wind in the direction of the station. Figure 10b shows the relative position of the station and firing point. The sound profile plot suggests that strong pressure amplification could be expected in the direction toward the recording station.

The recording station which is 8.3 km distant, showed a peak value of 126.7 db (44.5 Pa) which is higher than the pressure expected from the 1% exceedance at that distance (see Figure 8). This value is plotted in Figure 11 and a line was drawn through the point with the same slope as the 1% value. It represents the maximum expected value for muzzle blast from the 155 mm howitzer. It is used as the upper limit, or rare event. An upper limit curve for the 8" howitzer was scaled from the 155 mm data point. Measurements at 0 degrees from the angle of fire may show a somewhat higher reading but that geometry is not considered to be a typical proving ground configuration. Residential structures in the line of fire would not be close enough to sustain damage.

Ballistic Waves From Projectiles

The ballistic wave or "bow" shock developed when projectiles exceed the speed of sound account for pressures that are at times believed to be from HE shell or muzzle blast. At angles close to the line of fire the pressure from the ballistic wave can be higher than that from muzzle blast, but the character of the wave is different. Bow shock has a sharp but short pressure signal. Muzzle blast, having traveled a longer time has undergone more distortion by the atmosphere. In most scenarios bow shock can be disturbing, but not a damaging mechanism. An artillery shell, between launch and near apogee will be supersonic and the bow shock will be directed upward. Some projectiles will exceed the speed of sound as they fall toward their impact zone, directing the blast downward. The distance between impact zone and residential housing is most often sufficient to attenuate the bow shock to a non-damaging level.

Buried Munitions

A large percentage of claims received involve damage from the detonation f buried explosives. Explosives that are buried to the extent that no enting occurs (completely contained) will produce a very low grade "earth essure pulse" which is caused by the upward motion of the ground over the arge. It is unlikely that this pressure pulse will cause a problem. The likely scenario occurs with charges that vent to the atmosphere and the degree of venting will be unknown. Demolition activity most often involves several hundred pounds of explosives placed in pits and covered with an unspecified amount of earth. Detonation of the explosives causes the earth cover to lift, degrading the blast to some degree, but releasing substantial blast with the potential to cause problems.

In 1982 the White Engineering Associates made airblast and ground shock measurements from a series of typical DEMIL events at the MacAlester Army Ammunition Plant in Oklahoma. Measurements were made close in and out to a distance of 17 km in all four compass quadrants. They derived an equation from the data and established a maximum probable pressure-distance relationship. Figure 12 is a plot of that relationship for 1 kg and for 227 kg (500 lbs.), the amount of explosives frequently detonated in a DEMIL event. There are indications that all DEMIL operations are not conducted with the same degree of care. The most unfavorable condition would be no burial at all and no pit. If that were the case the charge weight would effectively be doubled and the relationship in Figure 5 would apply.

Blast/Structure Interaction

The blast/structure interaction is very difficult to define in the low pressure region. The blast from distant explosions is likely to be refracted downward by the atmosphere to strike the roof and walls of the structure at undefined angles, and the original sharp shock front has more than likely been degraded to some form of a compressional wave. One must deal with a structure in a pressure "environment" rather than attempt to determine loading on the different surfaces of a structure. Damage will have to be inferred from the pressure environment.

A structure responding to the blast environment deforms in a complex manner that depends on many factors that will not be available to the claim reviewer. Experiments by Siskind et al. [5], showed that the measured frequencies of residential structures and their midwalls were between 4 and 11, and 11 and 26 Hz respectively. Small explosive yields will have greater effect on midwalls than on the more massive structural sections. The midwall response is responsible for pictures being knocked from walls and knickknacks toppling from shelves. Siskind relates peak overpressure to midwall velocity and shows that at very weak pressures, <69 Pa (.01 psi), midwall velocities can exceed 51 mm/s (2 in/s). This can produce an acceleration of .5 g's which is sufficient to cause noticeable rattling. Precariously placed items could be knocked from shelves at this "g" level.

Airblast Damage Criteria

The low pressure region in which residential homes may experience light damage has not been of interest to the military, hence there is virtually no military data base from which to draw. However, in the early 1960's, the FAA was interested in the effects of a "sonic boom," which would be generated by the proposed flying of a supersonic transport (SST) across the country. The sonic boom pressure pulse is a low magnitude pulse with a duration of tens of milliseconds and, in that respect, it is not unlike the blast problems of interest here. In those experiments, residential homes were instrumented with transducers for the measurement of structural response to the pressure field imposed by a number of aircraft flying at supersonic speeds. The FAA-sponsored experiments concluded that it was improbable that a 144.7 Pa (.021 psi, or 137 db) pressure pulse would cause even slight damage to a residential type structure [6]. The reference, authored by Wiggins, summarizes much of the FAA-sponsored work and contains a chart showing minor and major damage that could be expected at various pressure levels. Table 1 is a reproduction of that chart with the pressure values converted from psf to Pa. While the FAA experiments included aircraft of various weights flown at different Mach numbers to vary the duration of the pressure pulse, the conclusion by Wiggins does not associate the damage level with the duration of the pressure wave.

In 1980, Siskind et al. [7] conducted experiments to determine the response of structure to ground vibration and airblast from surface mining. They link damage to residential homes to the type of home and the frequency content of the blast wave. With due consideration given to structural response and frequency content of the blast wave, he suggests that at a scaled distance equal to .32 km/kg$^{1/3}$, there should be no damage, if no consideration is given to amplification by atmospheric conditions. This equates to 187 Pa (.027 psi) which is consistent with the results of the "sonic boom" study.

The damage threshold criteria currently used in claim evaluations is 138 Pa (.02 psi). This value is 20 Pa less than the minimum value shown in Table 1. The lower value is an adjustment to account for structures that are subjected to repeated blasts and for those with sub-standard design or construction.

Typical Damage Claims

Most claim files will state that explosions caused some type of light damage such as broken windows, cracked plaster or knickknacks broken when knocked from shelves. This type of damage is what one would expect from low pressure blast. Many claims, however, will seek payment for concrete slabs and masonry basement walls. Often the claimant hears the blast, hears a picture or knickknack fall and then looks for further damage. He then finds cracks in masonry and thinks the blast caused that as well.

Claims of damage are frequently received from owners of mobile homes. Often these homes are made semi-permanent by supporting them with concrete or cinder blocks. These are inadequate supports in many cases because too few are used, placing excessive or uneven loads on them. In time, uneven settlement causes stresses to build to the point that paint may flick or even a window may crack. A low level blast may well trigger damage if the structure is already in a high state of stress.

This prestressing of a structure is not unique to mobile homes. Files will show that homes of high value often have cracked foundations which will cause misalignment of the structure to the extent that doors will not properly close or windows become stuck. Photographs, often furnished with a claim file, will at times show downspouts that empty directly to the soil in close proximity to the area of a cracked foundation. More than likely the localized high moisture content of the soil, coupled with freeze and thaw cycles caused the foundation to crack. It would be most unusual for one to evaluate a claim where airblast or ground motion would be high enough to damage a foundation. Such a claim would also show substantial above ground damage. It is not uncommon to review a claim where the government is blamed for causing below grade foundation damage, but no window breakage or damage to objects being knocked from shelves. This would be an obvious case of foundation damage that is not related to explosive activity.

Ground Shock

The claim file will often state that damage was caused by ground shock, but rarely will one encounter a legitimate ground shock claim. Wiggins [6] describes results of sonic boom experiments showing the ground shock developed by the sonic boom pulse striking the earth and concludes that airblast induced ground shock is negligible. An extrapolation of the referenced data shows that 137 Pa (.02 psi) blast would cause only .46 mm (.018 in/s) particle velocity in the earth. Humans can detect movement at velocities as low as .25 mm/s (.01 in/s) so they may sense the motion but it is not the damage mechanism. The Bureau of Mines [9] reports that earth particle velocities less than 50.8 mm/s (2 in/s) will not cause damage. For the types of explosions of interest here, those not completely confined, airblast effect will override the ground shock effects unless the charge is heavily confined and close to the structure.

Summary

Figure 13 is a plot showing the distance at which damage could be expected from typical ordnance activities on a day when meteorological effects would provide a maximum increase in pressure. Such days are rare, but possible. The plot for the 155 mm muzzle blast is the maximum muzzle blast plot shown on Figure 11. The 8" muzzle blast plot is scaled from that. Muzzle blast from the 8" howitzer could shake items from shelves in houses that are 7 km distant. The blast from a 155 mm HE round could do the same at the same distance. Structures more distant than 5 km from gun firings, impact areas, or properly executed DEMIL events would not expect structural damage. It should be noted that normal testing events, following established procedures will rarely cause structural damage to distant structures and that firings can continue without incidence on days when meteorological conditions do not enhance pressure.

Contd

This paper recommends "safe from damage" distances for typical military blast-producing events. Your criticism of these distances and your recommendations for improved damage criteria is invited. The Army wants to be fair to its neighbors and it wants just and defensible criteria.

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Table 1. Maximum Safe Predicted Peak Overpressures for Representative Building Materials and Bric-a-Brac Other than Glass

	WHITE SANDS	
MATERIAL	MINOR	MAJOR
INTERIOR WALLS AND CEILINGS	pa	pa
PLASTER ON WOOD LATH	158	620
PLASTER ON GYPLATH	358	765
PLASTER ON EXPANDED METAL LATH	765	765
PLASTER ON CONCRETE BLOCK	765	765
GYPSUM BOARD (NEW)	765	765
GYPSUM BOARD (OLD)	213	765
NAIL POPPING (NEW)	255	765
BATHROOM TILE (OLD)	213	406
DAMAGED SUSPENDED CEILING (NEW)	186	765
STUCCO (NEW)	234	765
BRIC-A-BRAC		
EXTREMELY PRECARIOUSLY PLACED OR UNSTABLE ITEMS	N/A	144
NORMALLY STABLE OR PLACED ITEMS	N/A	261
MISCELLANEOUS		
BRICK CRACKED	896	N/A
GLASS DOOR LOOSENED	896	N/A
TWISTED MULLIONS	427	N/A
POPPED MOLDING	896	N/A

STATIC CHARGE FIRINGS - ABOVE GROUND FOR RESEARCH AND DEMONSTRATION

DEMIL - OLD EXPLOSIVES IN A PIT AND COVERED WITH EARTH

DEMOLITION - DESTRUCTION OF TOWERS, BRIDGE SUPPORTS, ETC. (OFF RESERVATION)

TANK GUNS - 105 MM AND 120 MM GUNS (MUZZLE BLAST, HE AND BALLISTIC SHOCK)

ARTILLERY - 105 MM, 155 MM AND 8 IN. HOWITZERS (MUZZLE BLAST, HE AND BALLISTIC SHOCK WITH SELECTED SCENARIOS)

FIGURE 1. MILITARY ACTIVITIES PRODUCING BLAST WAVES

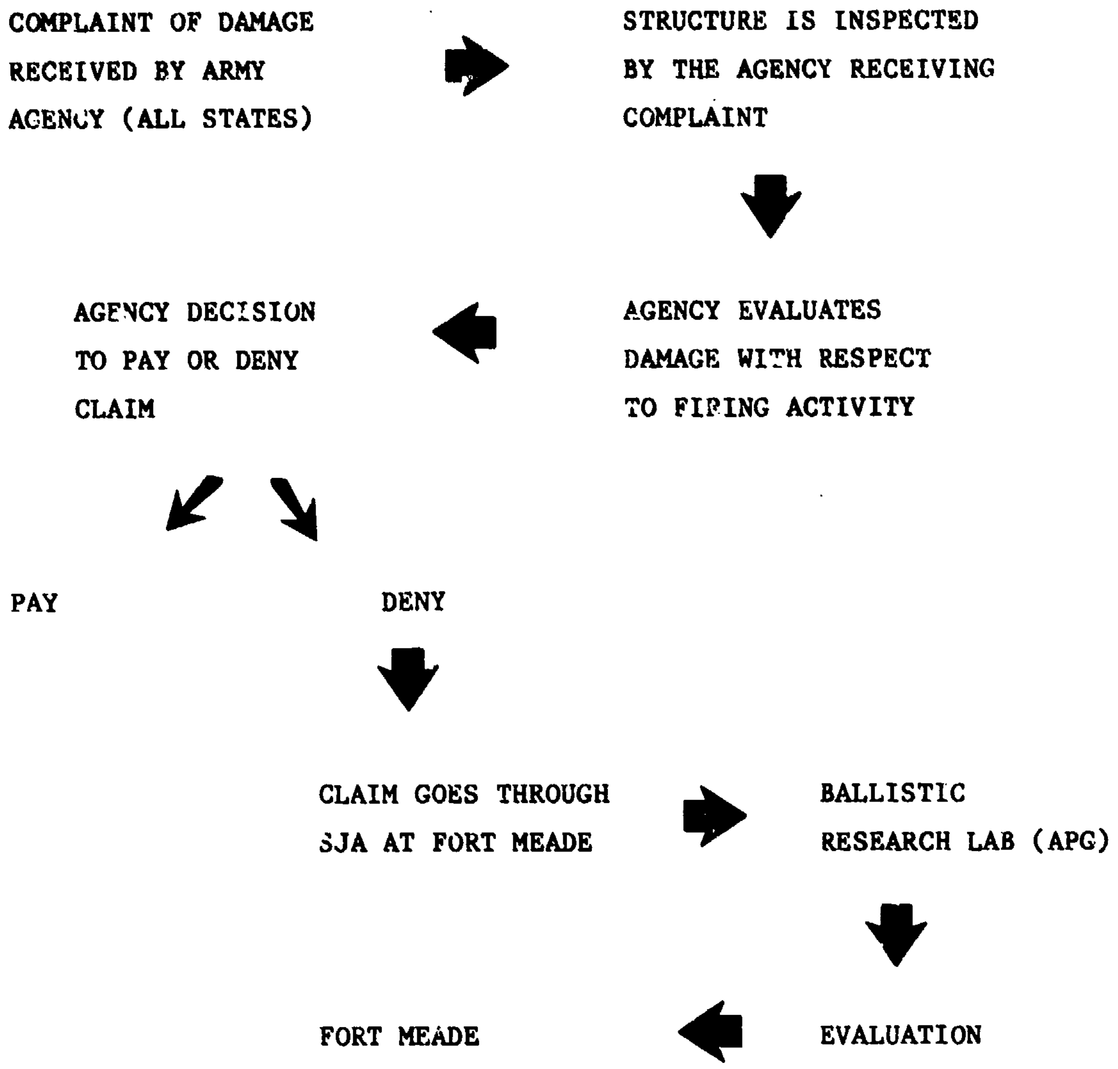

COMPLAINT OF DAMAGE RECEIVED BY ARMY AGENCY (ALL STATES)
STRUCTURE IS INSPECTED BY THE AGENCY RECEIVING COMPLAINT
AGENCY EVALUATES DAMAGE WITH RESPECT TO FIRING ACTIVITY
AGENCY DECISION TO PAY OR DENY CLAIM
PAY
DENY
CLAIM GOES THROUGH SJA AT FORT MEADE
BALLISTIC RESEARCH LAB (APG)
EVALUATION
FORT MEADE

FIGURE 2. COMPLAINT PROCEDURE

OBJECTS FALLING FROM SHELVES

MIRRORS AND PICTURES FALLING FROM WALLS

PAINT FLAKING

NAIL POPPING

DAMAGED SEALS IN THERMOPANE DOORS/WINDOWS

BATHROOM TILE

WINDOWS

BRICKWORK

FOUNDATIONS AND FOOTINGS

STRUCTURE MISALIGNMENT

PATIO/WALKS/SLABS

SWIMMING POOLS

WELLS

FIGURE 3. SPECTRUM OF DAMAGE CLAIMS

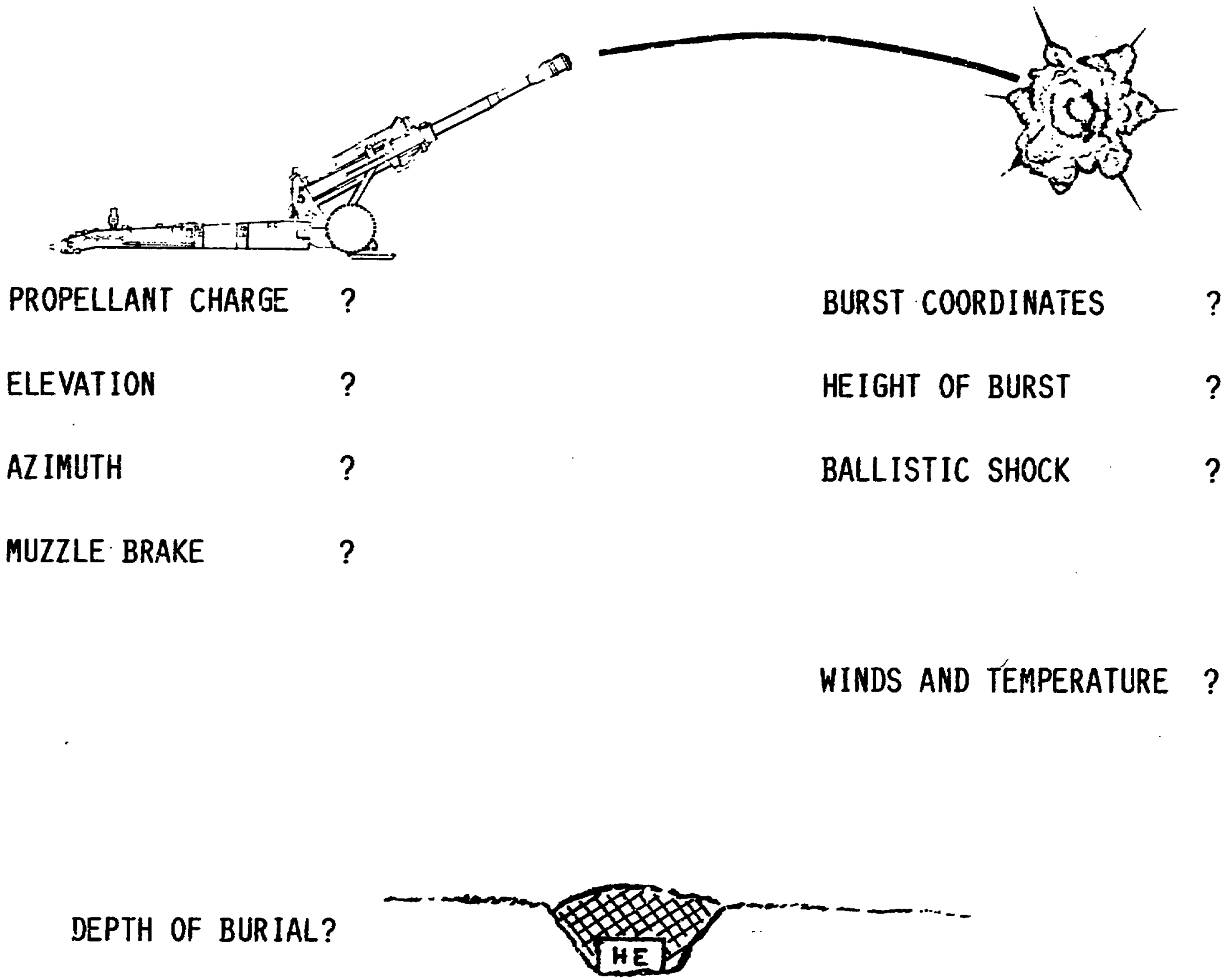


FIGURE 4. FREQUENT UNKNOWNS IN BLAST SCENARIOS

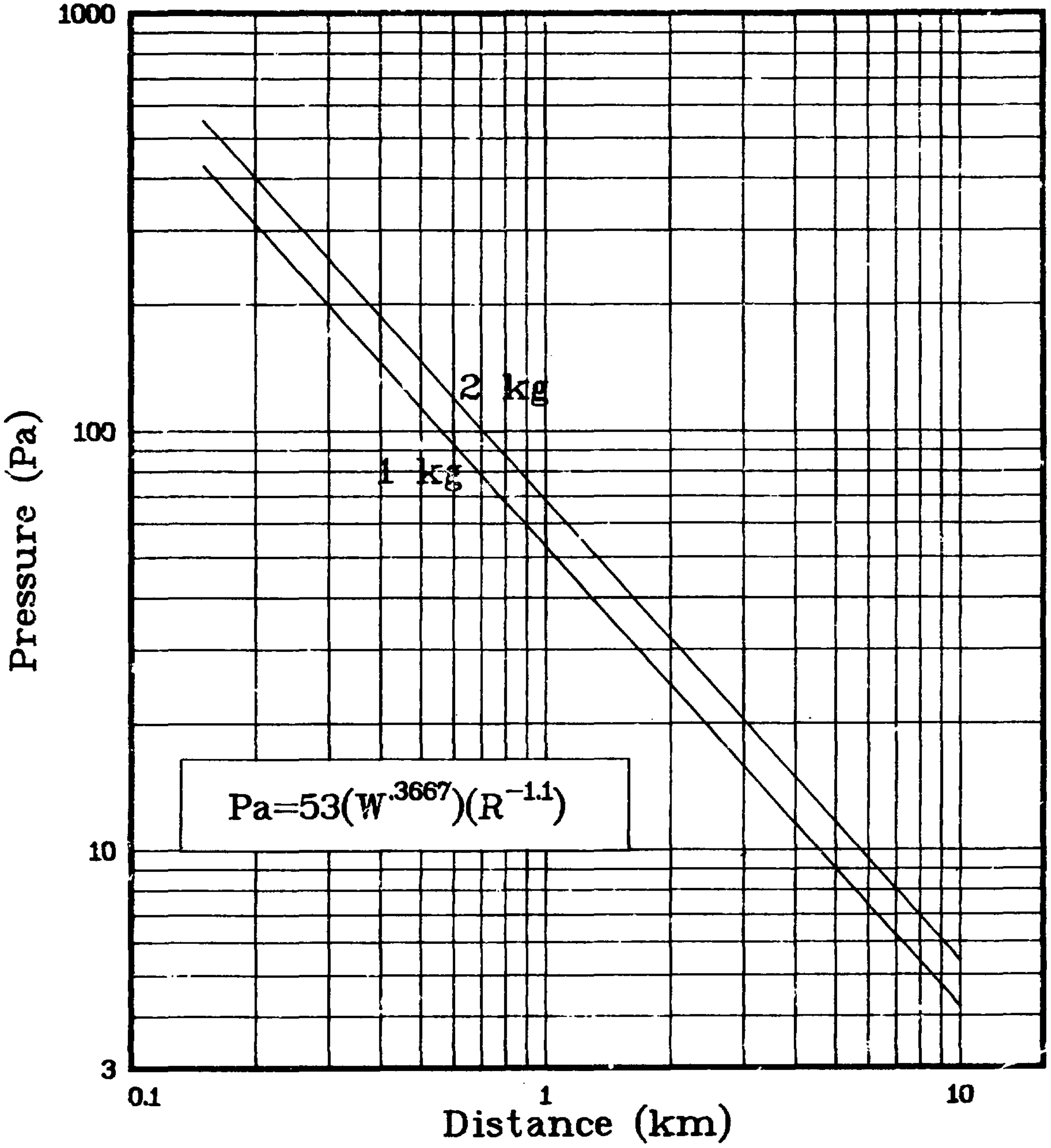


Figure 5. Explosion Pressure vs. Distance

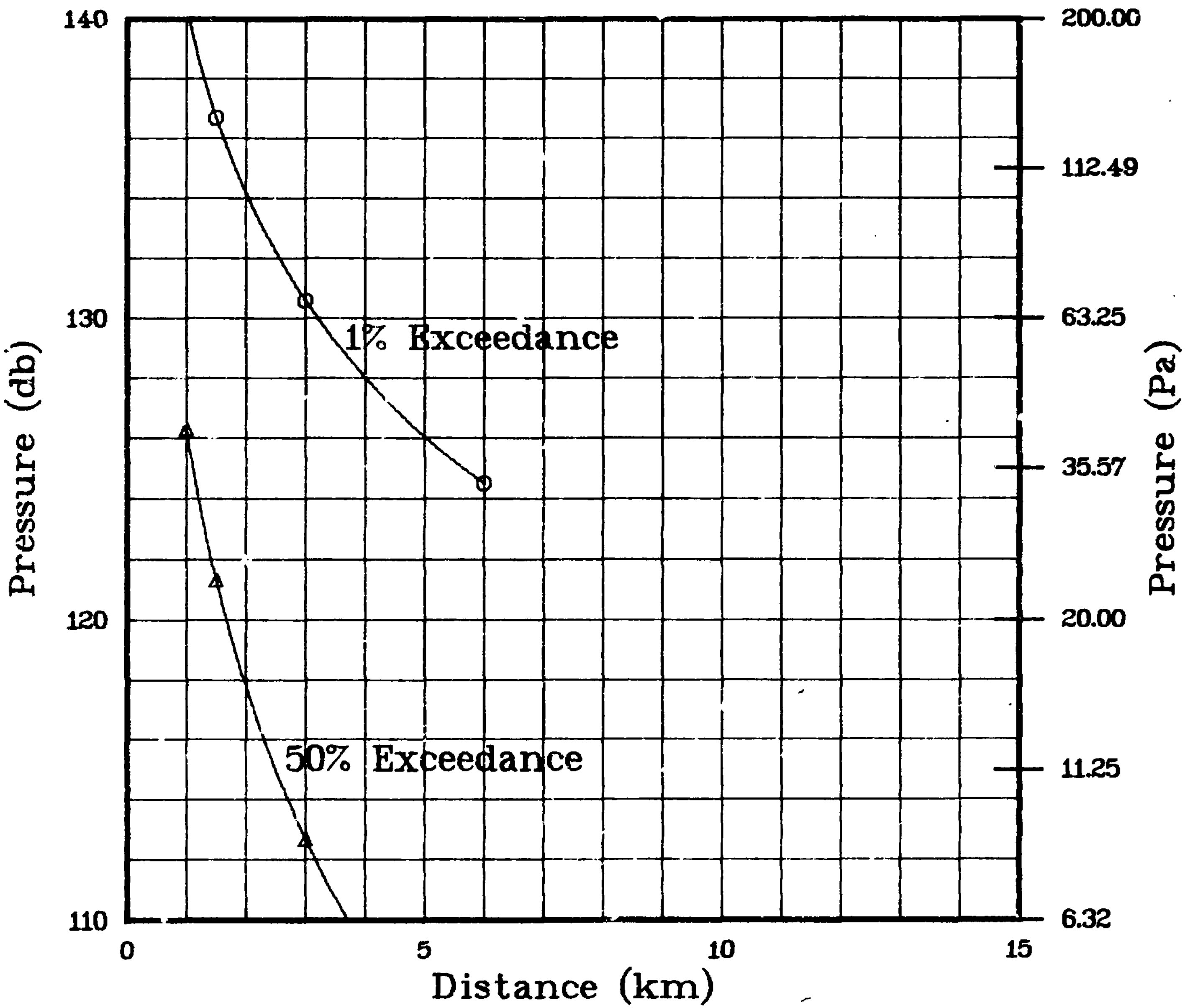


Figure 6. 120 mm Tank Gun Muzzle Blast. Pressure vs. Distance in Front of Gun

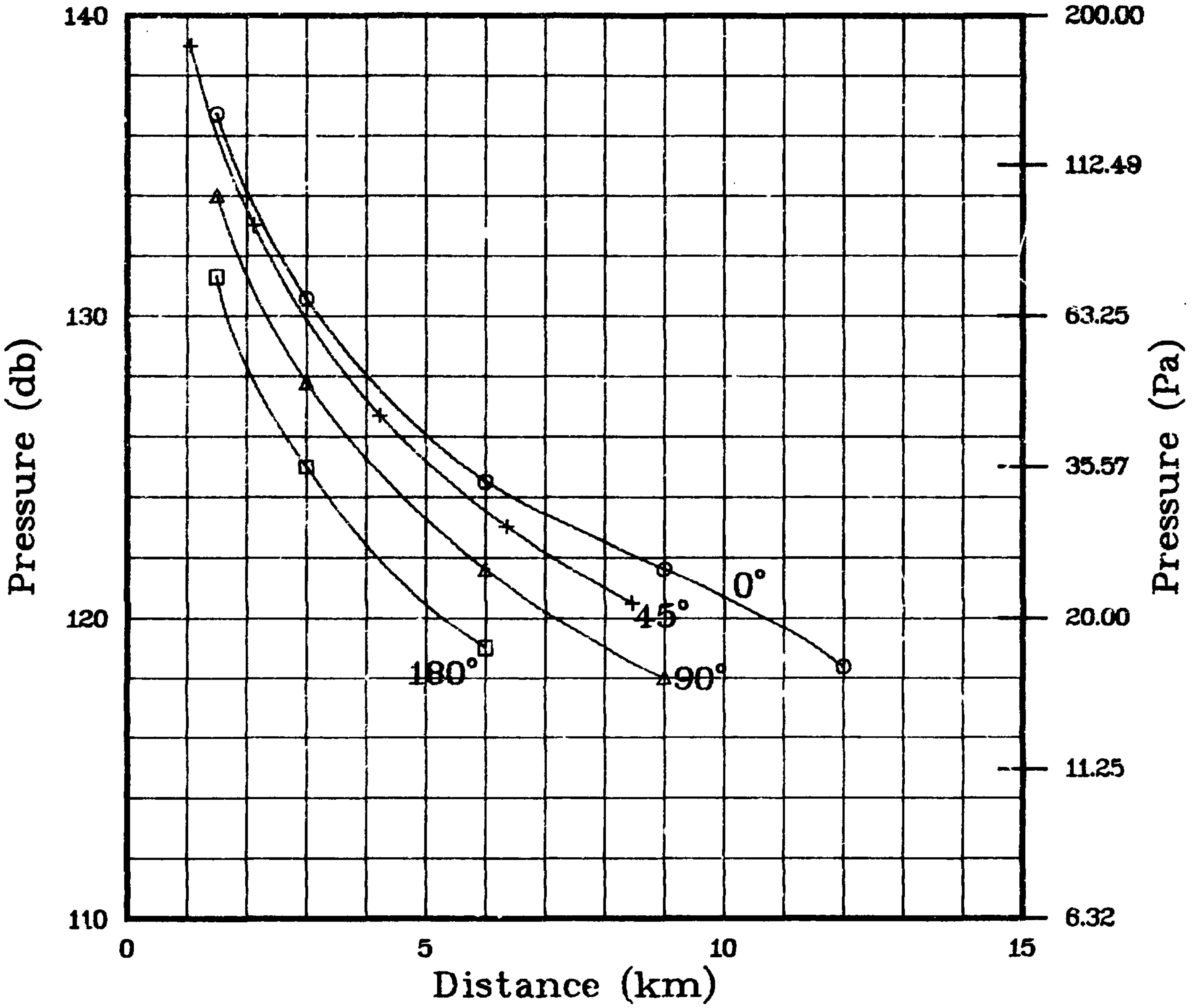


Figure 7. 120 mm Tank Gun, Pressure vs. Distance. 1% Exceedance at 0°, 45°, 90°, and 180°

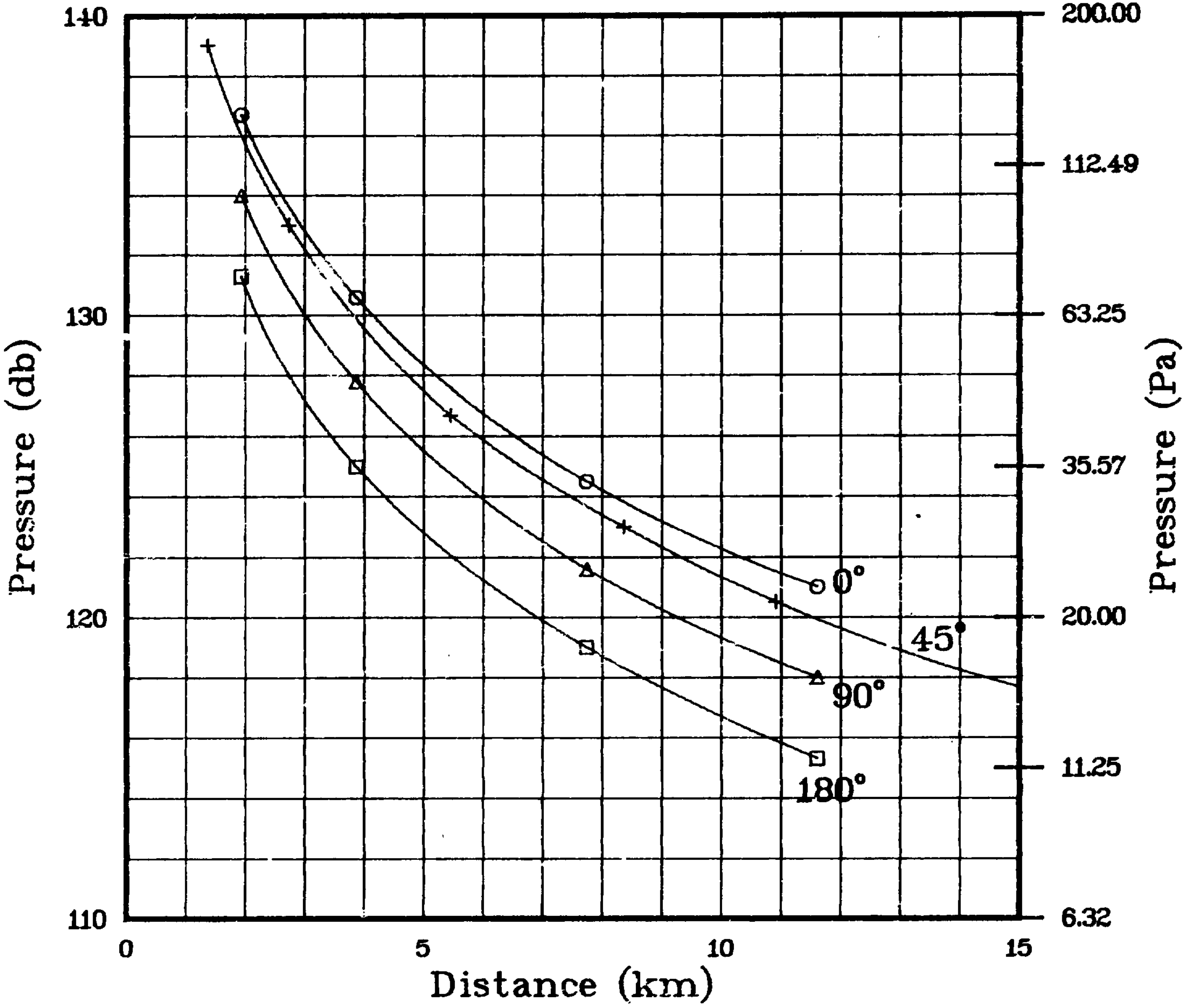


Figure 8. 155 mm Tank Gun, Pressure vs. Distance. 1% Exceedance at 0°, 45°, 90°, and 180°

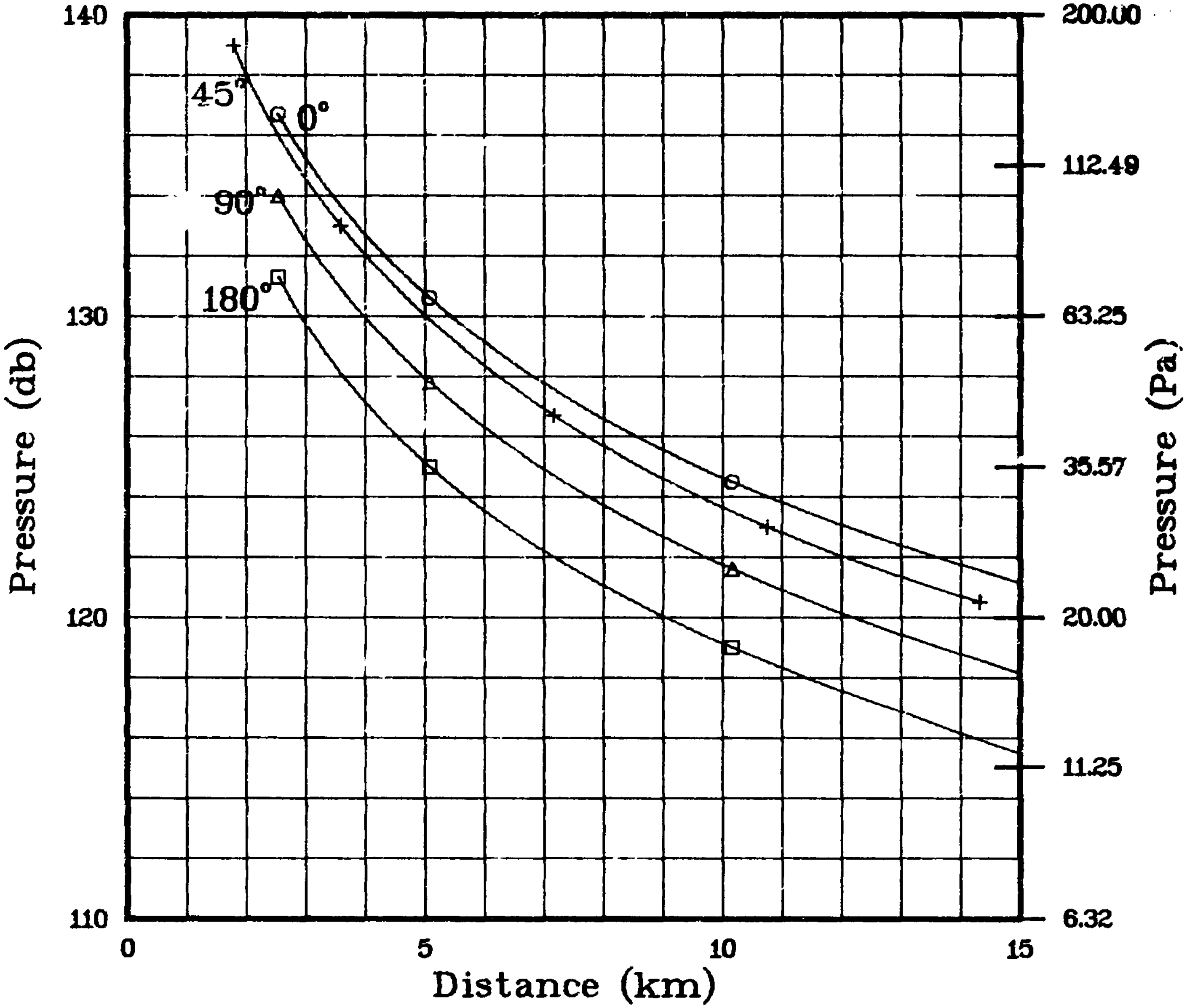
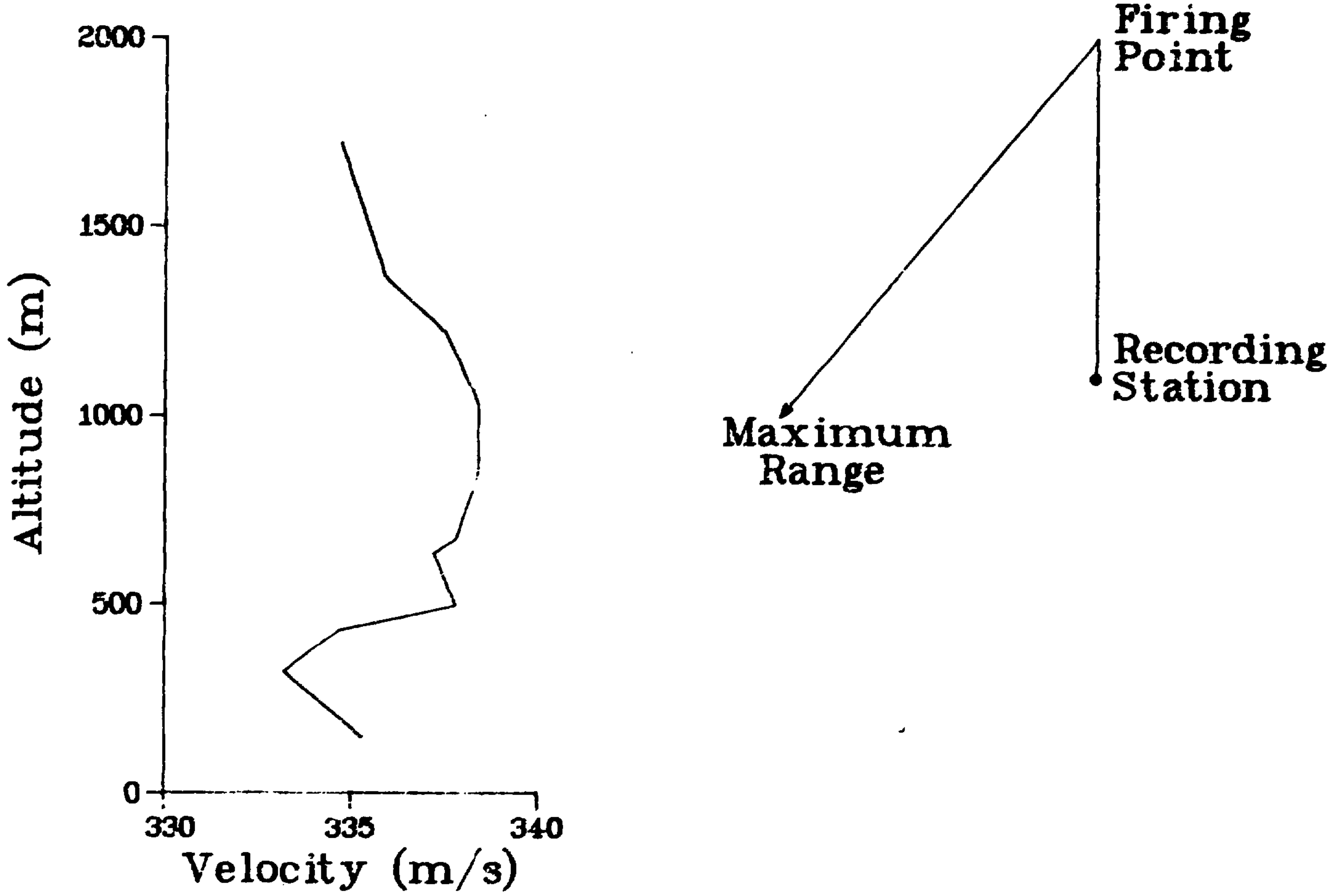


Figure 9. 8" Howitzer, Pressure vs. Distance. 1% Exceedance at 0°, 45°, 90°, and 180°



(A)

(B)

Figure 10. Sound Velocity Profile and Range Geometry

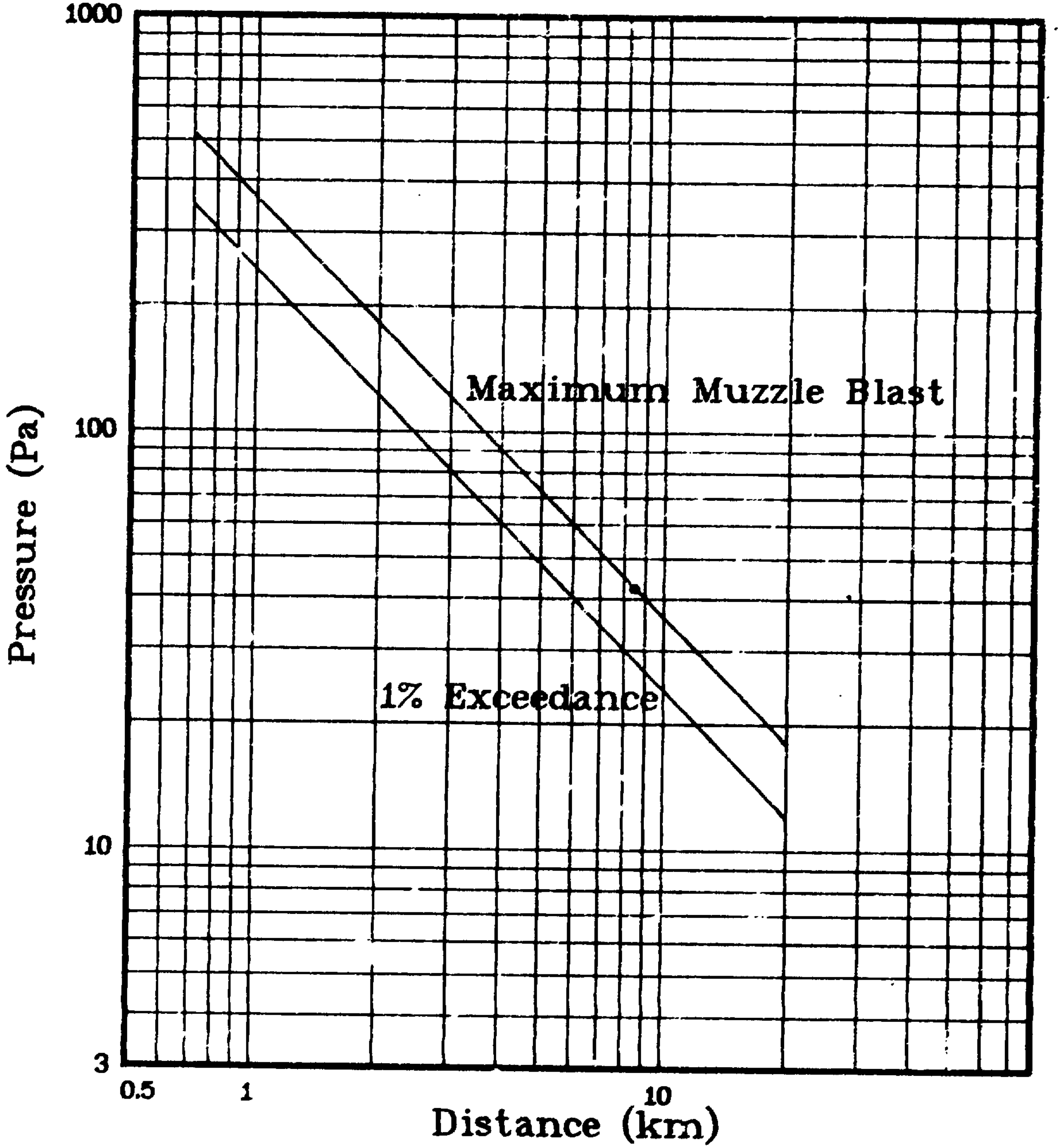


Figure 11. 1% Exceedance and Maximum Muzzle Blast from 155 mm Howitzer at 39°

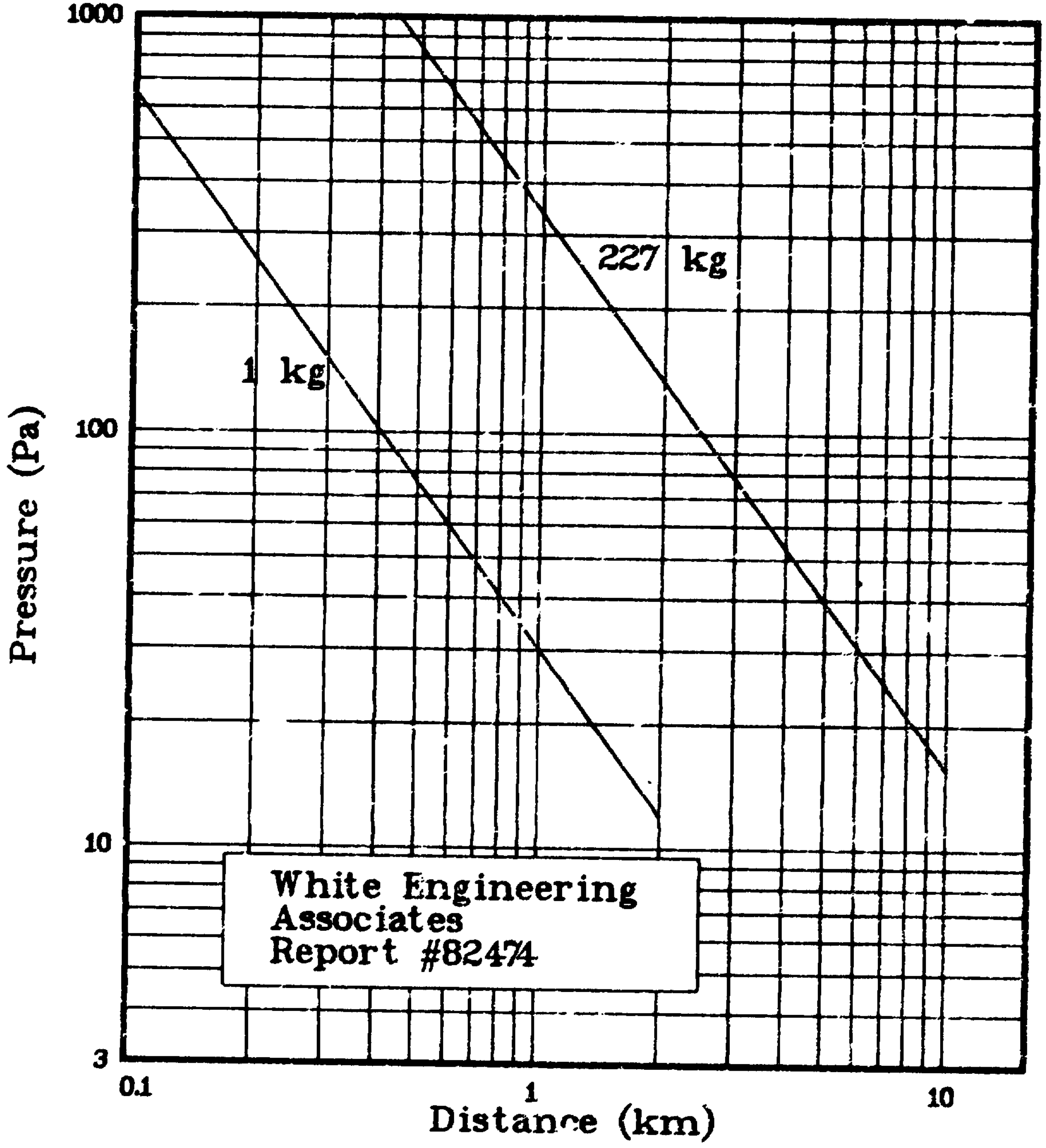


Figure 12. Maximum Probable Pressure from DEMIL Event

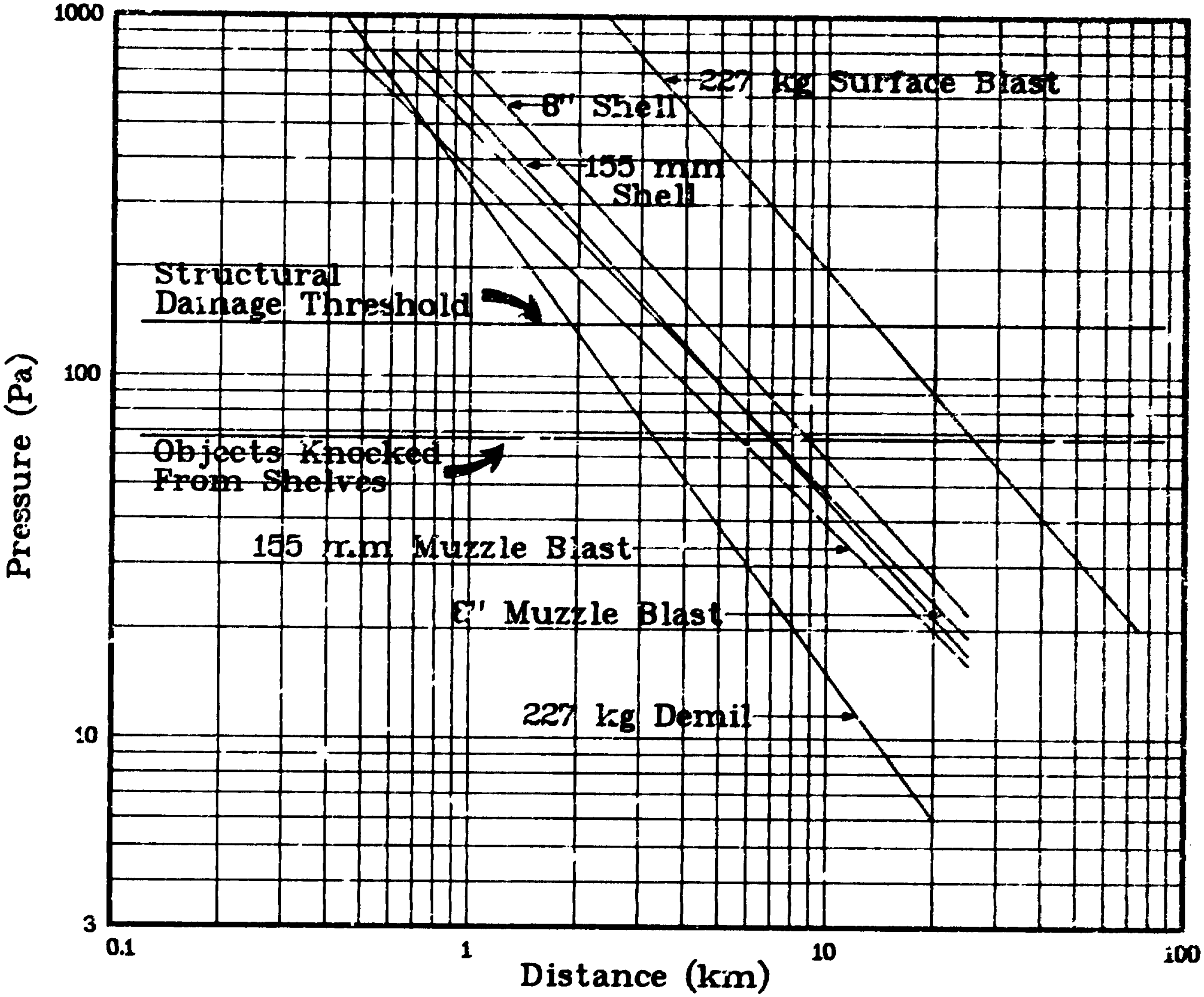


Figure 13. Critical Distance for Typical Ordnance Activities--Worst Case Meteorology

BLAST ANALYSIS AND PRELIMINARY DESIGN OF CONTROL ROOMS FOR THE ROCKET ENGINE TEST FACILITY AT NASA LEWIS RESEARCH CENTER

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ABSTRACT:

In support of plans to add a second control room to the Rocket Engine Test Facility at NASA Lewis Research Center, Cleveland, OH, the existing control room was analyzed to determine the most severe accidental explosion it could safely withstand. This potential accident was used as the design threat to develop a preliminary design for the new control room. The analysis and design calculations were based on procedures from the Army Technical Manual TM 5-1300/NAVFAC P-397/AFM 88-22, "Structures to Resist the Effects of Accidental Explosions," and the computer program CBARCS, which automates some of the procedures in the manual. To evaluate the degree of conservatism in the analysis, experimental data with charge weights and structural dimensions similar to the control room's were selected and analyzed. Results indicate that the existing room will safely withstand an explosion equivalent to 1,000 lb of TNT detonated at the rocket test stand 20 ft away. To survive the same accident, the new control room (to be constructed on top of the old one) should have 1-ft-thick walls (existing walls are 2 ft thick) with 0.33-percent reinforcement (existing walls have 1.55 percent). Comparison of data with analysis indicates that an accidental explosion equivalent to approximately 1,800 lb of TNT will cause unacceptable damage to the control room. This analysis results in a much more economical design for the new control room than would have been achieved by constructing a new room identical to the old control room. Also, comparing results of this analysis procedure with data provided a good estimate of safe operating criteria and the maximum capacity for the control rooms.

INTRODUCTION:

In June 1985, the NASA Lewis Research Center began preliminary engineering design work on the expansion of their Rocket Engine Test Facility. One option for this expansion is the construction of an additional control room on top of the existing control room. Because of the proximity of the control rooms to potentially high-explosive materials, it was decided that the existing control room should be analyzed to determine its blast resistance. It was also decided that the proposed additional room be designed with a compatible blast resistance. NASA requested that the USAE Waterways Experiment Station (WES) support this effort by providing a blast response analysis of the existing control room and preliminary design recommendations for the proposed additional control room.

SCOPE:

An analysis of the existing control room was accomplished using the "Computer Program for Optimum Nonlinear Dynamic Design of Reinforced Concrete Slabs under Blast Loading" (CBARCS). This code was developed under the sponsorship of the Office, Chief of Engineers (OCE), US Army, as a part of the Computer-Aided Structural Engineering (CASE) Project, and is available at the National Technical Information Service, Springfield, VA (Reference 1). Only the wall directly facing the potential explosion position was analyzed, and since the penetrations in this wall were less than 5 percent of the wall area, they were ignored. Enhancement of the reflected blast loading due to the floor and walls of the test chamber adjacent to the control room was included in the analysis. The analysis determined the response of the wall under various amounts of high explosive (HE) (TNT equivalent).

To evaluate the safety of the existing control room, data from recent experimental concrete slabs loaded by explosives under conditions similar to the existing and proposed control-room walls were examined. These data formed a basis for judgment as to the conservatism of the analysis procedures used

The design of the additional control room was also accomplished using the CBARCS program. Again, the wall facing the potential explosion position was considered the critical structural element. The CBARCS program optimization feature was used to iterate to a concrete thickness and a steel percentage which resulted in the most cost-effective structure. The explosion position was simplified by making the conservative assumption that the explosion took place at the elevation of the wall.

ANALYSIS OF EXISTING CONTROL ROOM:

The existing control-room wall was analyzed using the CBARCS program. This program uses yield line theory to analyze concrete slabs under high-explosive blast loads. The structure is idealized as a single-degree-of-freedom model. The program is consistent with the Army Technical Manual TM 5-1300, "Structures to Resist the Effects of Accidental Explosions" (Reference 2) and allows for the consideration of various slab edge conditions, penetrations, explosive types, explosive confinement, and reflection loading. It should be noted that this program is to be used for preliminary design and analysis only. Final design and analysis, including reinforcing details, should be in accordance with TM 5-1300.

Figure 1 shows the wall configuration and explosion position input into the CBARCS program for the existing control-room wall. The program output is shown in Appendix A. Results from different explosive weights indicate that a small increase in charge weight can result in a disproportionately greater increase in the corresponding wall deflection. Figure 2 shows this relationship and shows the charge weight which corresponds to various degrees of structural damage, i.e., in. of deflection.

TM 5-1300 indicates that a concrete slab without laced reinforcing is considered to fail at a 2-degree support rotation to avoid buckling of compressive steel. According to the CBARCS program, this amount of rotation takes place under an explosive load of 900 lb of TNT and is equivalent to 0.70-in. deflection. However, TM 5-1300 also states in Chapter 6, Section 6-2, that a category-1 protection wall for personnel protection is allowed a support rotation of 5 degrees for laced reinforcement. Past experience at WES has shown that a concrete slab reinforced with conventional shear stirrups can sustain a support rotation of at least 5 degrees without failure. This does not prove that the control-room wall in question could rotate 5 degrees without failure, but it does point out the relative conservatism of the 2-degree rotation criteria.

COMPARISON OF ANALYSIS WITH EXPERIMENTAL DATA

The safety of the CBARCS analysis of the existing control-room wall can be evaluated by using data from a recent series of experiments conducted by Mr. Mark McVay at WES. The purpose of these tests was to evaluate different antispalling schemes for a concrete wall loaded by a cased TNT charge. Two of the experiments closely simulate the conditions of the existing control-room wall.

The first experiment was conducted at a scale of 1/2.8 of the control-room wall. This scales up to a 24-in.-thick wall loaded by a cased charge of 444 lb of TNT at a range of 14.12 ft (Figure 3). The flexural steel ratio was 0.25 percent with a steel strength of 60,000 psi and a concrete strength of 5,200 psi. Shear resistance was provided by 0.152 in. per linear ft of 60,000-psi shear steel. This is comparable to the control-room wall with a thickness of 24 in. and a steel ratio of 1.55 (considerably more than the 0.25 ratio in the test slab) with a steel strength of 40,000 psi and a concrete strength of 3,000 psi. Shear steel consisted of 0.40 sq in. per linear ft, 40,000-psi steel for the control room. To judge the conservatism of the CBARCS program, the program was used to analyze the experimental wall (Appendix B). This analysis will be directly compared to the experimental results.

The pressure history as measured at the bottom of the experimental wall is shown in Figure 4. The total effective impulse calculated by CBARCS was 792.64 psi-msec, while the scaled impulse from the experimental wall, measured at the position closest to the explosion, was 1,288 psi-msec. Because the control-room wall has a natural period of 30.4 msec, the wall is impulse sensitive; therefore, the loading by CBARCS is comparable to that of the experiment. It should be noted that the CBARCS program applies a uniform loading function over the entire surface of the wall. In the experimental case, the pressure was seen to attenuate substantially at increasing distances away from the source of the explosion. This indicates that CBARCS makes a conservative estimate of the loading function. The CBARCS structural response calculations are also shown to be conservative when the program predicts that the experimental wall should fail in flexure, with a support rotation of 2.3 degrees. The data from the experiment shows that there was essentially no damage to the wall (Figure 5).

The second experiment was conducted at a scale of 1/4.47 of the control-room wall. This scales up to a 24-in.-thick wall loaded by a charge of 1,755 lb of TNT at a range of 22.32 ft (Figure 6). The flexural steel ratio was 0.25 percent with a steel strength of 60,000 psi and a concrete strength of 4,000 psi. Shear steel consisted of 0.24 sq in. per linear ft, 60,000-psi steel. The CBARCS program was again used to analyze the experimental wall. This analysis showed that the wall collapsed with a support rotation of 12 degrees (Appendix C). The results of the experimental test were moderate damage and flexural response corresponding to approximately a 1.2-degree support rotation (Figure 7).

The final conclusion as to the capacity of the existing control-room wall is based on the CBARCS analysis and experimental data. The CBARCS program indicates that the control-room wall will withstand 900 lb of TNT before it will fail in flexure. However, when shear is checked as per TM 5-1300, the shear steel required is greater than that which exists in the wall. The experimental data indicate otherwise. In both experiments, the shear steel present was less than that in the control-room wall, yet diagonal shear failure did not occur. This supports a perception widely held by WES experimenters that the problem of shear failure is overestimated in TM 5-1300 and other similar blast-design manuals. Also, a comparison of the flexural response predicted by CBARCS for the experimental walls and the actual response of these walls shows the extreme conservatism present in the CBARCS program (Figure 8). Therefore, it is recommended that based on the experimental data the capacity of the existing control-room wall be considered to be 1,000 lb of TNT.

DESIGN OF ADDITIONAL CONTROL ROOM:

The design of the additional control room was simplified by considering only the wall facing the potential explosive (Figure 9). This wall was designed using the CBARCS program and TM 5-1300. The structural optimization feature of the CBARCS program was used to develop the least-cost wall to resist the given load. A detailed explanation of the optimization feature can be found in the CBARCS User's Guide (Reference 1). Briefly, the program takes an assumed cost for steel and concrete; sets up a cost function; and with an assumed starting point, increments the design variables until a minimum cost is obtained.

The CBARCS program's input and output can be seen in Appendix D. A concrete strength of 4,000 psi and a steel strength of 60,000 psi was used. No laced shear reinforcement was assumed; therefore, the 2-degree support rotation failure criteria was used. In the first computer run, 1,000 lb of TNT was assumed to explode at the elevation of the wall with no floor or wall reflections. The wall was assumed to be fixed at all supports. This resulted in the computer iterating down to the minimum wall thickness of 12 in. and the minimum steel ratio allowed by the program and recommended by TM 5-1300.

With these results, it was decided that a more economical design may be possible. The preliminary design of the proposed control room assumed that the wall facing the explosion hazard was tied into a floor slab to be constructed on top of the existing control room. This would mean that the roof of the existing control room and the new slab would have a combined thickness of 3 ft of concrete. This is grossly overdesigned. If the existing roof could be used as the proposed floor, a cost savings would result. There is, however, no economical way to make a moment-transferring connection between the proposed wall and the existing control room. This means that the bottom of the proposed wall must be treated as a pinned connection or as a free edge, if we are going to do away with the floor slab.

The CBARCS design program was rerun, assuming that the bottom was a free edge (Appendix E). Again, the concrete strength was 4,000 psi, and a steel strength of 60,000 psi was used. This resulted in a design which required a 12-in.-thick wall with a vertical and horizontal flexural steel requirement of 0.33 percent on both sides. These are nearly the same requirements as for the fixed-edge case above. In the actual design, it is recommended that shear studs be provided to connect the proposed wall to the existing control room, providing a pinned connection at that point. These shear studs must be able to resist a shear of 13,100 lb per linear ft as per the shear present at the bottom support in the fixed-edge computer run. Shear stud requirements are dependent upon the stud layout and geometry chosen by the designers. However, examination of the literature shows that a reasonable shear stud design is possible for this loading. Diagonal shear reinforcement in the wall slab must be provided at 0.22 sq in. per linear ft in both directions, with a minimum spacing of 12 in. In this way, a safe design can be assured even though the actual pinned condition falls somewhere between the fixed- and free-edge conditions which were directly analyzed.

CONCLUSION:

The analysis of the existing control-room wall using the CBARCS program and TM 5-1300 resulted in a safe design load of 900 lb of TNT equivalent at a range of 20 ft. This is a conservative estimate due to the 2-degree support rotation requirement for unlaced concrete slabs and the conservatism of the CBARCS program. This conservatism is exemplified by a recent experiment where reinforced concrete walls under roughly comparable conditions showed no damage after testing. Also, reinforced concrete walls tested under much more severe conditions exhibited moderate damage and indicated a maximum allowable amount of explosive corresponding to about 1,800 lb of TNT at a range of 20 ft. The experiments in question did not model the enhancement of the blast loading due to reflection from adjacent walls; however, the moderate damage which resulted allows us to recommend that a load of 1,000 lb of TNT should be considered the capacity of the existing control-room wall.

Design calculations for the proposed additional control room using 1,000 lb of TNT equivalent indicated a required wall thickness of 12 in. with a flexural requirement of 0.33-percent steel vertically and horizontally on each side. The concrete strength was 4,000 psi, and the steel yield strength was 60,000 psi with 3 in. of cover concrete. Shear stirrups are required at 0.22 sq in. per linear ft with a minimum spacing of 12 in. Shear studs are required to tie the proposed control room into the existing concrete. The studs must resist a shear force of 13,100 lb per linear ft.

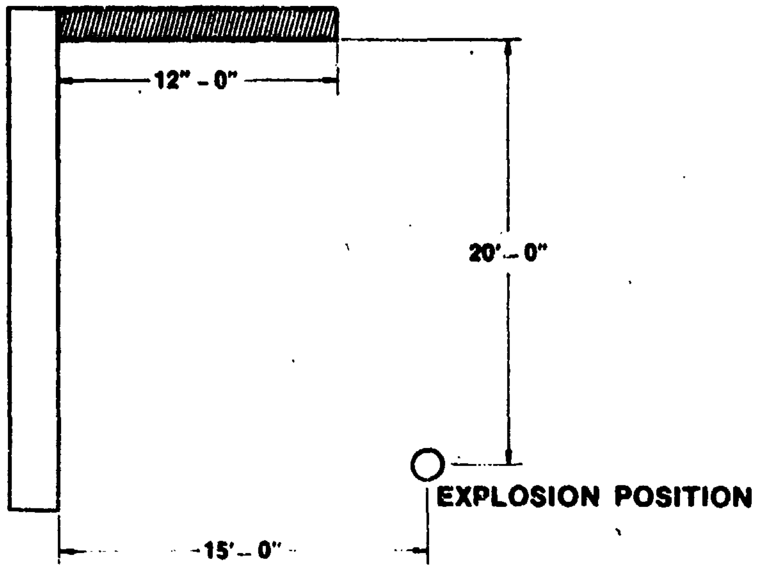

Figure 1. Wall and explosive position input into CBARCS for existing control-room wall.

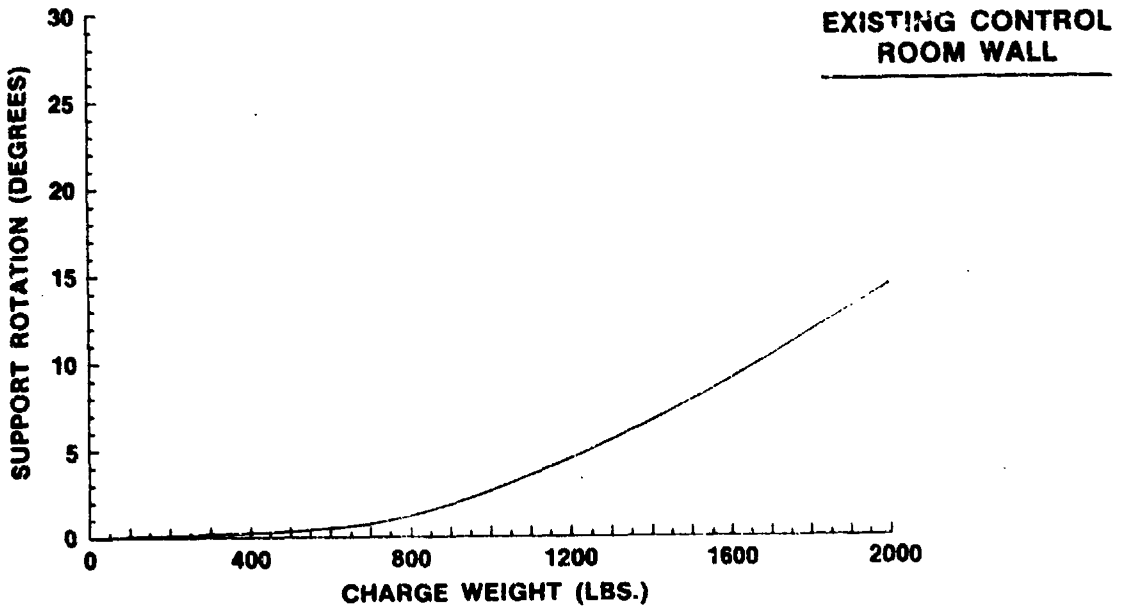

Figure 2. Charge weight versus CBARCS calculated deflection for existing control room.

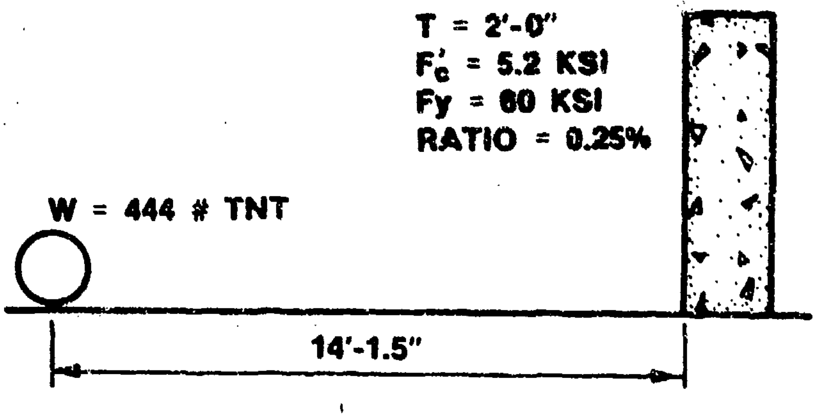

Figure 3. Layout of Experiment 1 scaled up for comparison with existing control room wall.

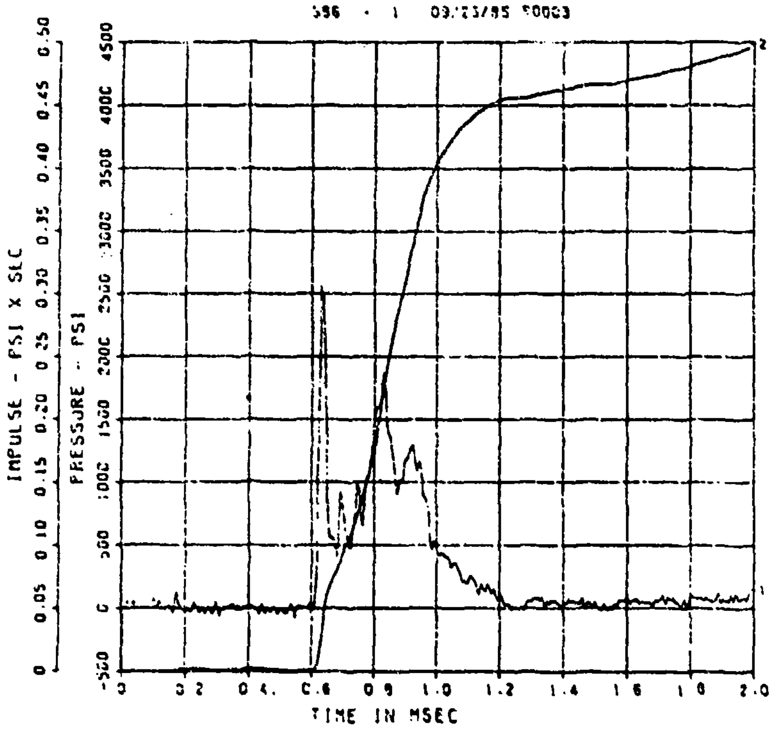

Figure 4. Pressure history for Experiment 1.

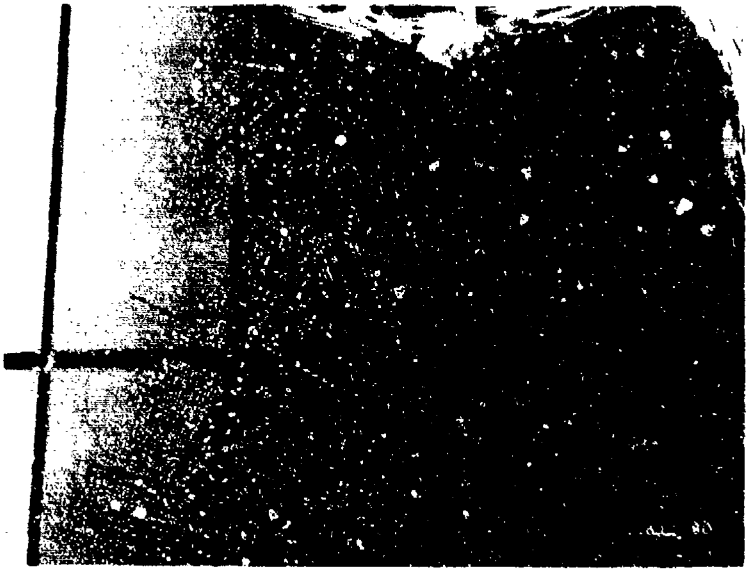

Figure 5. Posttest damage to inside of test wall, Experiment 1.

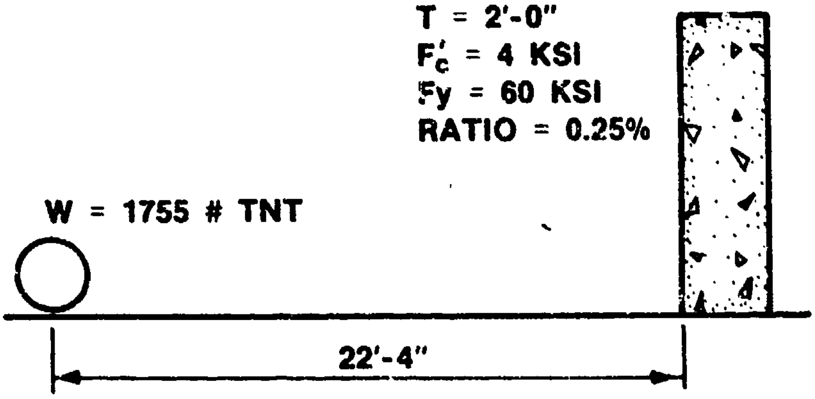

Figure 6. Layout of Experiment 2 scaled up for comparison with existing control-room wall.

Figure 7. Posttest damage to inside of test wall, Experiment 2.

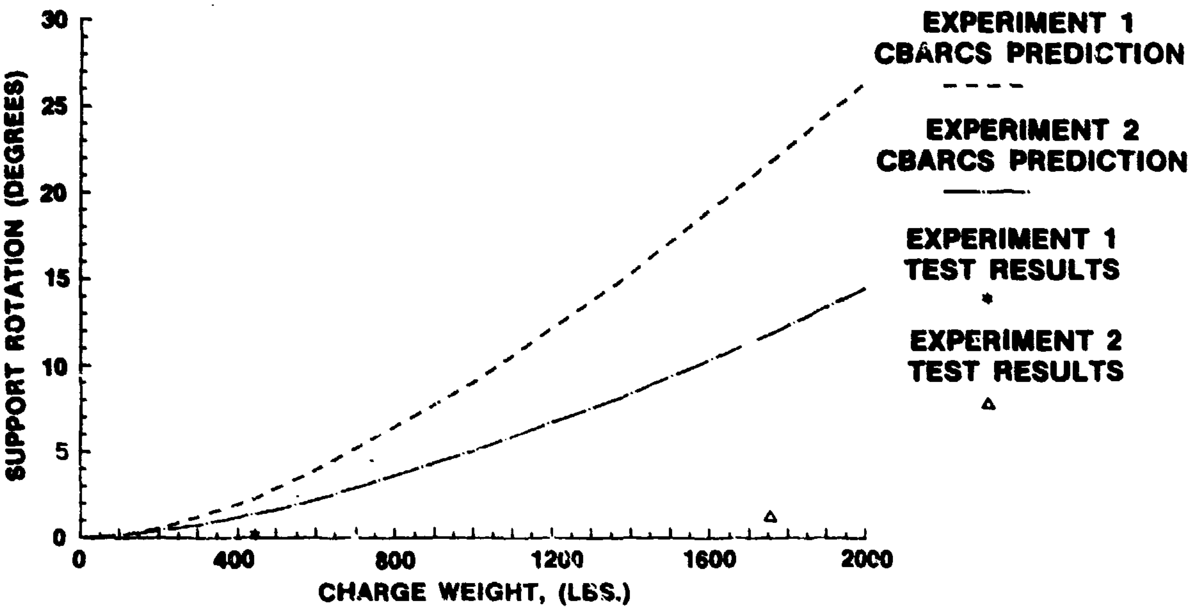

Figure 8. Comparison of CBARCS calculated deflection to experimental data.

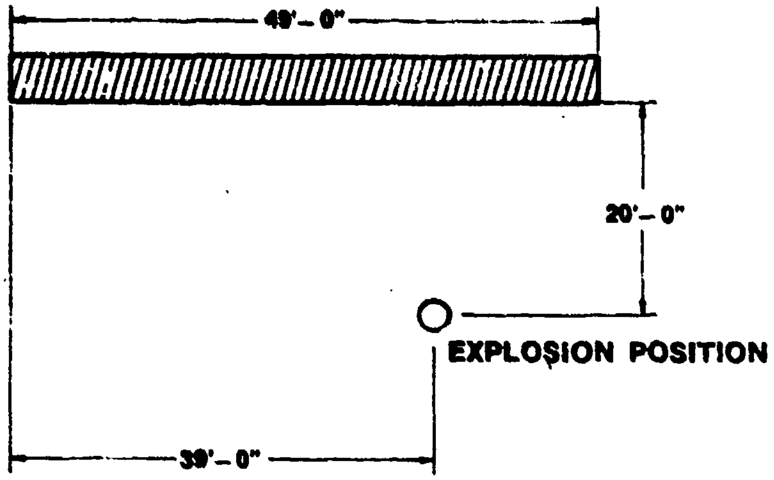

Figure 9. Wall and explosive position input into CBARCS for proposed control-room wall.

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1. J. M. Ferritto, Robert M. Wamsley, and Paul K. Senter; "User's Guide: Computer Program for Optimum Nonlinear Dynamic Designs of Reinforced Concrete Slabs Under Blast Loading (CBARCS)" Instruction Report K-81-6, USAE Waterways Experiment Station, Vicksburg, MS, March 1981.

2. "Structures to Resist the Effects of Accidental Explosions" TM 5-1300, NAVFAC P-397, AFM 88-22, Department of the Army, Navy, and Air Force, June 1969.

Design Criteria for Blast Resistant Thermally Tempered Glazing

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INTRODUCTION

Historical records of explosion effects demonstrate that blast-propelled glass fragments from failed windows are often a major cause of injuries from explosions. Also, failed window glazing often leads to additional injuries as blast pressure can enter interior building spaces and subject personnel to high pressure jetting, incident overpressure, secondary debris impact and thrown body impact. These risks are heightened in modern facilities, which often have large areas of glass.

Guidelines are presented for the design, evaluation, and certification of fixed or non-openable windows to survive safely a prescribed blast environment described by a triangular-shaped pressure-time curve. Window designs using monolithic (unlaminated) thermally tempered glass based on these guidelines can be expected to provide a probability of failure equivalent to that provided by current safety standards for safely resisting wind loads.

The guidelines are presented in the form of load criteria for the design of both the glass panes and framing system for the window. The criteria account for both bending and membrane stresses and their effect on maximum principal stresses and the nonlinear behavior of glass panes. The criteria cover a broad range of design parameters for rectangular-shaped glass panes. Design charts are presented for monolithic thermally tempered glazing with blast overpressure capacity up to 100 psi, an aspect ratio $1.00 \leq a/b \leq 4.00$, pane area $1.0 \leq ab \leq 25$ ft^2, and nominal glass thickness $1/4 \leq t \leq 3/4$ inches. An alternate method for blast capacity evaluation by calculation is also presented. This can be used to evaluate blast capacity of glass when interpolation between charts is unadvisable, when design parameters are outside the limits of the chart values, and to calculate rebound loads. Presently, the design criteria are for blast-resistant windows with thermally treated, monolithic tempered glass. Further research is required to extend these design criteria to laminated tempered glass.

BACKGROUND

The design criteria cover monolithic thermally tempered glass meeting the requirements of Federal Specifications DD-G-1403B and DD-G-451d. Additionally, thermally tempered glass is required to meet the minimum fragment weight requirements of ANSI Z97.1-1984, Section 5.1.3(2).

Annealed glass is the most common form of glass available today. Depending upon manufacturing techniques, it is also known as plate, float or sheet glass. During manufacture, it is cooled slowly. The process results in very little, if any, residual compressive surface stress. Consequently, annealed glass is of relatively low strength when compared to tempered glass. Furthermore, it has large variations in strength and fractures into dagger-shaped, razor-sharp fragments. For these reasons, annealed glass is not recommended for use in blast-resistant windows.

Thermally tempered glass is the most readily available tempered glass on the market. It is manufactured from annealed glass by heating to a high uniform temperature and then applying controlled, rapid cooling. As the internal temperature profile relaxes towards uniformity, internal stresses are created. The outer layers, which cool and contract first, are set in compression, while internal layers are set in tension. As it is rare for flaws, which act as stress magnifiers, to exist in the interior of tempered glass sheets, the internal tensile stress is of relatively minimal consequence. As failure originates from tensile stresses exciting surface flaws in the glass, precompression permits a larger load to be carried before the net tensile strength of the tempered glass pane is exceeded. Thermally tempered glass is typically four to five times stronger than annealed glass.

The fracture characteristics of tempered glass are superior to those of annealed glass. Due to the high strain energy stored by the prestress, tempered glass will eventually fracture into small cube-shaped fragments instead of the razor-sharp, dagger-shaped fragments associated annealed glass. Breakage patterns of side and rear windows in American automobiles are a good example of the failure mode of thermally or heat-treated tempered glass.

Semi-tempered glass is often marketed as safety or heat-treated glass. However, it exhibits neither the dicing characteristic upon breakage nor the higher tensile strength associated with fully tempered glass. Semi-tempered glass is not recommended for blast-resistant windows.

Another common glazing material is wire-reinforced glass, annealed glass with an embedded layer of wire mesh. Its only use is as a fire-resistant barrier. Wire glass has the fracture and low strength characteristics of annealed glass and, although the wire binds fragments, it contributes metal fragments as an additional hazard. Wire glass is never recommended for blast-resistant windows.

DESIGN CRITERIA FOR GLAZING

Specified Glazing

The design of blast-resistant windows is currently restricted to heat-treated, fully-tempered glass in fixed or non-openable frames meeting both Federal Specification DD-G-1403B and ANSI Z97.1-1984. Tempered glass meeting only DD-G-1403B may possess a surface precompression of only 10,000 psi. At this level of precompression, the fracture pattern is similar to annealed and semi-tempered glass. Tempered glass meeting the minimum fragment specifications of ANSI Z97.1-1984 (Section 5.1.3(2)) has a higher surface precompression level and tensile strength which improves the capacity of blast-resistant windows. Additionally, failure results in smaller, cubical-shaped fragments.

Although thermally tempered glass exhibits the safest failure mode of any glass, failure under blast loading still presents a significant health hazard. Results from blast tests reveal that upon fracture, tempered glass fragments may be propelled in cohesive clumps that only fragment upon impact into smaller rock-salt-shaped fragments. Even if the tempered glass breaks up initially into small fragments, sufficient blast pressure can propel the fragments at a high enough velocity to constitute a severe danger. Because of the high likelihood of multiple edge and corner impacts by fragments of tempered glass, biomedical experts warn that the 58-ft-lb criterion for acceptable fragments should not be applied. Because of these fragment dangers, blast-resistant glazing should be designed to survive with high probability its design threat.

Design Stresses

The design stress, the maximum principal surface tensile stress allowed for the glazing, f_u, is set at 16,000 psi. This correlates with a probability of failure equal to or less than 0.001.

The design stress for blast-resistant glazing is slightly higher than that commonly used in the design for 1-minute wind loads. However, this is justified on the basis of the short high stress duration (always considerably less than 1 second) experienced by the glazing. This beneficial effect of less ceramic fatigue has been confirmed by recent testing by the National Research Council of Canada.

Dynamic Response to Blast Load

An analytical model was used to predict the blast load capacity of monolithic (single sheet) tempered glazing. Characteristic parameters of the model are illustrated in Figure 1.

The glazing is a rectangular, fully thermally tempered glass plate having a long dimension, a; a short dimension, b; a thickness, t; a poisson ratio, $\nu = 0.22$; and an elastic modulus, $E = 10,000,000$ psi. The plate is simply supported along all four edges, with no in-plane or rotational restraints at the edges in accordance with observed window edge conditions. The stiffness of the supporting frame members is assumed to be infinite relative to the pane. Recent static and blast load tests indicate that the design allowable frame member deflections of 1/264th of the span will not significantly reduce pane resistance from that predicted for an infinitely stiff frame.

The blast pressure loading is described by a peak triangular-shaped overpressure-time curve as shown in Figure 1b. The blast pressure rises instantaneously to a peak blast overpressure, B, and then decays linearly with a blast pressure duration, T. The pressure is assumed to be uniformly distributed over the surface of the plate and applied normal to the plate.

The resistance function r(X) (static uniform load, r, as a function of center deflection, X) for the plate accounts for both bending and membrane stiffness. The effects of membrane stresses produce nonlinear stiffening of the resistance function as illustrated in Figure 1c. The design deflection, X_u, is defined as the center deflection where the maximum principal tensile stress at any point in the glass first reaches the design stress, f_u, of 16,000 psi. Typically, as the deflection of the pane exceeds a third of its thickness, the points of maximum stress will migrate from the center of the pane towards the corners.

The model uses a single-degree-of-freedom system to simulate the dynamic response of the plate, as shown in Figure 1d. To be conservative, no damping of the window pane is assumed. The applied blast load, B(t), is shown in Figure 1b. The resistance function, r(X), is shown in Figure 1c. Given the design parameters for the glazing, the design stress, f_u, and the blast load duration, T, the model calculates the peak blast pressure, B, required to exceed the prescribed probability of failure of 0.001. The model also restricts the center deflection to no more than ten times the glazing thickness. This restricts solutions to the valid range of the Von Karmen plate equations used to develop the resistance function.for the glazing while also preventing edge disengagement of the glass lite.

Design Charts

Charts are presented in Figures 2 through 22 for both the design and evaluation of glazing to survive safely a prescribed blast loading with a probability of failure no greater than 0.001. The charts relate the peak blast overpressure capacity, B, of thermally tempered glazing to all combinations of the following design parameters: a/b = 1.00, 1.25, 1.50, 1.75, 2.00, 3.00, and 4.00; $1.00 \leq ab \leq 25$ ft^2; $12 \leq b \leq 60$ inches; $2 \leq T \leq 1{,}000$ msec; and t = 1/4, 5/16, 3/8, 1/2, 5/8, and 3/4 inch (nominal). Thermally tempered glass up to 3/4 inch thick can be easily purchased in the United States. Thicknesses greater than

3/4 inch can only be obtained by lamination. Research and blast load testing are required to develop design curves with confidence for laminated glass.

Each chart has a series of curves. Each curve corresponds to the pane dimension shown to the right of the curve. Adjacent to the pane dimension is the value of B (peak blast overpressure capacity) corresponding to T = 1,000 msec. The posted value of B is intended to reduce errors when interpolating between curves.

The charts are based on the minimum thickness of fabricated glass allowed by Federal Specification DD-G-451d. However, the nominal thickness should always be used in conjunction with the charts, i.e., t = 1/4 inch instead of the possible minimum thickness of 0.219 inch used in design. The third column of Table 2 reports the minimum design thickness used in place of the nominal thickness. The charts are created by numerically integrating the equations of motion of a single-degree-of-freedom system as modeled in Figure 1d. A Wilson-Theta technique was employed with a time step corresponding to no greater than 1/25th of each of the five increasing linear resistances used to model the actual resistance function.

Alternate Design Procedure

The following design procedure can be used to evaluate design blast capacity, B, of monolithic tempered glass when interpolation between charts is unadvisable, when design parameters are outside the range of parameters in the design charts, or when calculating rebound loads. By iterating on trial pane sizes, this procedure can also be used for design. It is recommended that the design charts be used to make an initial guess at the glass thickness. The procedure also calculate the parameters required for rebound calculations.

This section imparts how to calculate design resistance, r_u, design deflection, X_u, the effective elastic static resistance of a equivalent linear responding pane, r_{eff}, effective pane stiffness, K_e, and the fundamental period of vibration, T_n. With these parameters calculated, the presented response charts can be used to calculate dynamic response under blast load and design blast capacity. Table 6 reports the fundamental period of vibration, T_n, and Equation 7 reports the effective elastic static resistance, r_{eff}, for most dimensions of glass panes. In many cases, especially if interpolating between design charts, these values can be read directly from their respective tables. The single equation in Step 10 of the Alternate Design Procedure can then be used directly to compute blast overpressure capacity, B.

Step 1. Calculate whether the glass pane will behave as a linearly responding plate under its design load. If the ratio of the short side of the pane, b, to its actual or design (not nominal) thickness is less than the maximum in the second column of Table 3, then simple formulas can be used to calculate the parameters needed to enter the dynamic response charts. Only glass panes of the encompassed dimensions and thicknesses above and to the left of the stepped line in Table 1 will qualify. If the glass pane has a b/t ratio less than that specified in Table 3, the glass will behave in a nonlinear manner with membrane stresses induced by straining of the neutral plane or axis of the plate. Proceed to steps 2 through 9 for a simplified procedure for calculating key parameters of this nonlinear plate behavior.

For glass panes qualifying as behaving with a linear response, the following formula can be used.

For a lineraly behaving pane, both the design static and the effective elastic static design resistance, r_{eff}, is defined as:

$$r_{eff} = r_u = C_r(t/b)^2, \text{ psi} \qquad (1a)$$

The design center deflection of the pane can be calculated as:

$$X_u = C_D (b^2/t) \qquad (1b)$$

The coefficients for computing the effective design resistance, C_r, and the design center deflection, C_D, are listed in Table 3.

The fundamental period of vibration for the pane is calculated as:

$$T_n = C_T(b^2/t) \qquad (2)$$

Coefficient C_T is reported in the last column of Table 3. With these parameters calculated, proceed to step 10 to enter the dynamic response charts to calculate blast capacity.

Step 2. For nonlinear behaving glass panes with a b/t ratio greater than specified in the second column of Table 3, calculate the nondimensional design stress, S_{ND}, as:

$$S_{ND} = 0.0183(b/t)^2 \qquad (3)$$

where: b = short span of the glass measured between center lines of the gaskets, inches
t = actual thickness of the glass in inches. The measured or design thickness should be used rather than the nominal thickness. Table 2 presents the design thicknesses.

For values of a/b greater than 4, use a/b = 4.

Step 3. Enter Figure 23 with the value of S_{ND} and a/b. Read the nondimensional design load, L_{ND}.

Step 4. Calculate the static design resistance, r_u, as:

$$r_u = 876{,}000(L_{ND})(t/b)^4, \text{ psi} \qquad (4)$$

This value should be used in all frame design calculations. However, the effective static design resistance, r_{eff}, defined in Step 7, should be used for rebound design.

Step 5. Enter Figure 24 with a/b and the value of L_{ND} and read the nondimensional deflection X/t. The nondimensional deflection, X/t, shall not exceed 10. If X/t exceeds 10, use the value of L_{ND} corresponding to X/t of 10 to recalculate r_u using Figure 23.

Step 6. Calculate the design center deflection of the glass pane, X_u, as:

$$X_u = (X/t)\ t, \text{ inches} \tag{5}$$

Step 7. Calculate the effective elastic static design resistance, r_{eff}, of an equivalent linearly responding pane as:

$$r_{eff} = 0.4(r_1 + r_2 + r_3 + r_4 + 0.5\ r_u), \text{ psi} \tag{6}$$

where: r_1 = resistance at 0.2 X_u

r_2 = resistance at 0.4 X_u

r_3 = resistance at 0.6 X_u

r_4 = resistance at 0.8 X_u

r_u = resistance at X_u (r_u obtained from Step 4)

X_u = value obtained from step 6

Figures 24 and 23 should be used to calculate r_1 through r_4. The equivalent static design load is the resistance that a linear responding plate would exhibit with the same strain energy as the actual nonlinear behaving plate at the design center deflection, X_u. It is always less than the design static resistance, r_u. By employing a linear equivalent system for dynamice analysis, the linear response charts can be used with reasonable accuracy.

Step 8. Calculate effective stiffness, K_E, as:

$$K_E = r_{eff}/X_u, \text{ psi/in} \tag{7}$$

Step 9. Calculate the fundamental period of vibration of the glazing, T_n, as:

$$T_n = 2\pi\sqrt{\frac{K_{LM}\,m}{K_E}}, \text{ msec} \tag{8}$$

where K_{LM} is the load mass factor of the glass:

$K_{LM} = 0.63 + 0.16(a/b - 1) \qquad 1 \leq a/b \leq 2$

$K_{LM} = 0.79 \qquad a/b \geq 2$

The unit mass of the glass, m, is:

$m = 233\ t,\ \text{lb-ms}^2/\text{in}^3$

Step 10. Enter the dynamic response chart in Figure 25a (identical with Figure 3-49 of Volume No. 1 of NAVPAC P-397 draft) with the ratio of the effective duration of the blast load to the fundamental period of vibration of the glass pane, T/T_n. Read the dynamic load factor, D_{LF}, which is the ratio of the maximum stress produced by the dynamic peak blast pressure to the maximum stress from a statically applied peak pressure. The blast overpressure capacity, B, of the glass pane can be defined as:

$$B = r_{eff}/D_{LF} \tag{9}$$

For T/T_n ratios greater than 10, set D_{LF} to 2. For ratios less than 0.05, set D_{LF} to 0.3.

REQUIRED DESIGN CRITERIA FOR FRAME

Sealants, Gaskets, and Beads

All gaskets or beads are required to be at least 3/8 inch wide with a Shore "A" durometer hardness of 50 and conform to ASTM Specification C509-84 (Cellular Elastomeric Preformed Gasket and Sealing Material).

The bead and sealant are required to form a weatherproof seal.

Glazing Setting

Minimum frame edge clearances, face clearance, and bite (illustrated in Figure 26) are specified in Table 3.

Frame Loads

The window frame must develop the static design strength of the glass pane, r_u, given in Table 1. Otherwise, the design is inconsistent with frame assumptions, and the peak blast pressure capacity of the window assemblies predicted from Figures 2 through 22 will produce a failure rate in excess of the prescribed failure rate. This results because frame deflections induce higher principal tensile stresses in the pane, thus reducing the capacity available to safely resist the blast loading.

In addition to the load transferred to the frame by the glass, frame members must also resist the static design load, r_u, applied to all exposed members. Maximum allowable limits for frame design are:

1. Deflection: No frame member should have a relative displacement exceeding 1/264th of its span or 1/8 inch, whichever is less.

2. Stress: The maximum stress in any member should not exceed $f_y/1.65$, where f_y = yield stress of the members material.

3. Fasteners: The maximum stress in any fastener should not exceed $f_y/2.00$.

The design loads for the glazing are based on large deflection plate theory, but the resulting transferred design loads for the frame are based on an approximate solution of small deflection theory for normally loaded plates. Analysis indicates this approach to be considerably simpler and more conservative than using the frame loading based exclusively on large deflection plate behavior, characteristic of window panes. The effect of the static design load, r_u, applied directly to the exposed frame members of width, w, should also be considered. The design load, r_u, produces a line shear, V_x, applied by the long side, a, of the pane equal to:

$$V_x = C_x r_u b \sin(\pi x/a) + r_u w, \text{ lb/in} \tag{10}$$

The design load, r_u, produces a line shear, V_y, applied by the short side, b, of the pane equal to:

$$V_y = C_y r_u b \sin(\pi y/b) + r_u w, \text{ lb/in} \tag{11}$$

The design load, r_u, also produces a corner concentrated load, R, tending to uplift the corners of the window pane equal to:

$$R = C_R r_u b^2, \text{ lb} \tag{12}$$

Distribution of these forces as loads acting on the window frame is shown in Figure 27. Table 4 presents the design coefficients, C_x, C_y, and C_R for practical aspect ratios of the window pane. Linear interpolation can be used for aspect ratios not presented.

Although frames with mullions are included in the design criteria, it is recommended that single pane frames be used.

Experience indicates that mullions complicate the design and reduce reliable fabrication of blast-resistant frames. If mullions are used in design, the certification test must be required as the complexity of the mullion cross sections may cause some of the assumptions standard in structural analysis to be unconservative relative to local shear and stress concentrations. Also, economic analysis indicates that generally thicker glass will be more cost effective than the more complex mullion frame. If mullions are used, the loads given by Equations 12, 13, and 14 should be used to check the frame mullions and fasteners for compliance with the deflection and stress criteria stated above. It is important to note that the design load for mullions is twice the load given by Equations 10 to 12 in order to account for effects of two panes being supported by a common mullion.

Special design consideration should be taken so that the deflection of the building wall will not impose deflections on the frame greater than 1/264th of the length of the edge of the pane. Where it is impossible to achieve enough building wall rigidity, it is recommended that the frames be pinned at the corners to the structure in a manner to isolate the frame from wall rotation.

Rebound

Response to the dynamic blast load, will cause the window to rebound with a negative (outward) deflection. The outward pane displacement and the stresses produced by the negative deflection must be safely resisted by the window while positive pressures act on the window. Otherwise, the window which safely resists stresses induced by positive (inward) displacements may fail in rebound while the positive pressure still acts. This can propel glass fragments into the interior of the structure. However, if the window fails in rebound during the negative (suction) phase of the blast loading, glass fragments will be drawn away from the structure. If glass failure does not present a hazard to personnel outside the structure, glass may be permitted to fail during the negative load phase. Rebound will occur during the negative load phase if the effective blast duration, T, is no greater than one half the natural period of vibration, T_n, of the glass pane. For $T \geq 10\ T_n$, significant rebound does not occur during the positive blast pressure phase. Therefore, rebound can be neglected as a design consideration. For $0.5 < T/T_n < 10$, the frame must be designed for the peak negative resistance occurring during the positive overpressure phase. Table 6 reports T_n for all practical glass pane dimensions.

As the rebound chart (Figure 3-268 in Volume III of draft NAVFAC P-397) can be unconservative in predicting maximum rebound, r^-, dynamic analysis using numerical integration will be required. In lieu of dynamic analysis, it is conservative to set the maximum rebound uniform load, r^-, to the static design load, r_u. The resistance function required for this analysis can be generated by using the Alternate Design Procedure. If the glass pane has a b/t ratio less than specified in Table 3, the pane will behave as a linear plate and Equations 1a and 1b can be used to calculate r_u and X_u and define the resistance function. If the pane has a b/t ratio larger than specified in Table 3, use Steps 2 through 7 to compute (r_1, 0.2 X_u), (r_2, 0.4 X_u), (r_3, 0.6 X_u), (r_4, 0.8 X_u) and (r_u, X_u) which define the resistance function. The negative resistance, modeling excursions of the pane in the outward direction, is the mirror image of the positive resistance function.

The portion of the frame outward of the glass must resist the maximum rebound uniform load, r^-. Equations 10 through 12 are used to apply the maximum rebound load to the frame members. In some design situations the resistance built into the member outboard of the glass to resist the corner concentrated force, R (calculated in Equation 10) during deflections of the pane inward will provide enough strength to resist rebound.

ACCEPTANCE TEST SPECIFICATION

Certification tests of the entire window assembly are required unless analysis demonstrates that the window design is consistent with the design criteria. All window assemblies using mullions must be tested. The certification tests consist of applying static uniform loads on at least two sample window assemblies until failure occurs in either the tempered glass or frame. Although at least two static uniform load tests to failure are required, the acceptance criteria presented below encourage a larger number of test samples. The number of samples, beyond two, is left up to the vendor. Results from all tests shall be recorded in the calculations. All testing shall be performed by an independent testing laboratory certified by the contracting officer.

Test Procedure - Window Assembly Test

The test windows (glass panes plus support frames) shall be identical in type, size, sealant, and construction to those furnished by the window manufacturer. The frame assembly in the test setup shall be secured in a manner that simulates the adjoining walls. Using either a vacuum or a liquid-filled bladder, an increasing uniform load shall be applied to the entire window assembly (glass and frame) until failure occurs in either the glass or frame. Failure shall be defined as either breaking of glass or loss of frame resistance. The failure load, $\hat{r}$, shall be recorded to three significant figures. The load should be applied at a rate of 0.5 r_u per minute which corresponds to approximately 1 minute of significant tensile stress duration until failure. Table 1 reports the static design resistance, r_u, for old tempered glass correlated with a probability of failure to be no greater than 0.001 and a stress intensity duration of 1 second. However, the new glass in the test procedure will be tested under a loading where the duration of significant net tensile stress will be about 1 minute. The longer duration of loading will weaken the glass through ceramic fatigue, while the use of new glass will tend to induce failure at a higher load capacity. To account for these variations from design conditions, the static load capacity of a glass pane for certification testing, r_s, is calculated as:

$$r_s = 0.876\, r_u \tag{13}$$

Acceptance Criteria

The window assembly (frame and glazing) are considered acceptable when the arithmetic mean of all the samples tested, $\bar{r}$, is such that:

$$\bar{r} \geq r_s + s\,\alpha \tag{14}$$

where: r_s = static load capacity of the glass pane for certification testing

s = sample standard deviation

α = acceptance coefficient

For n test samples, $\bar{r}$ is defined as:

$$\bar{r} = \frac{\sum_{i=1}^{n} \hat{r}_i}{n} \tag{15}$$

where $\hat{r}_i$ is the recorded failure load of the i^{th} test sample. The sample standard deviation, s, is defined as:

$$s = \sqrt{\frac{\sum_{i=1}^{n} (\hat{r}_i - \bar{r})^2}{(n - 1)}} \qquad (16)$$

The minimum value of the sample standard deviation, s, permitted to be employed in Equation 18 is:

$$s_{min} = 0.145\ r_s \qquad (17)$$

This assures a sample standard deviation no better than that observed for ideal tempered glass in ideal frames.

The acceptance coeffieient, α, is tabulated in Table 5 for the number of samples, n, tested.

The following equation is presented to aid the tester in determining if additional test samples are justified. If:

$$\bar{r} \leq r_s + s\,\beta \qquad (18)$$

then, with 90% confidence, the design will not prove to be adequate with additional testing. The rejection coefficient, β, is obtained from Table 5.

Certification for Rebound

The Acceptance Test Specification shall be performed for rebound unless analysis demonstrates the frame is consistent with rebound criteria. All frames with mullions must be tested. Testing is performed by executing the Acceptance Test Specification with the load applied to the inboard surface of the window assembly. The equivalent static rebound load, r^-, is substituted for the static design load, r_u.

INSTALLATION INSPECTION

A survey of glazing failures due to wind load indicates that improper installation of setting blocks, gaskets or lateral shims, or poor edge bite is a significant cause of failure because of the resultant unconservative support conditions. To prevent premature glass failure, a strenuous quality control program is required.

SAMPLE PROBLEMS

The following examples demonstrate the application of the design criteria in the design and evaluation of windows to safely survive blast overpressures from explosions.

Problem 1--Evaluation of Blast Capacity for Tempered Glass

Given: A control room at a bomb practice range has thermally tempered glass windows meeting both Federal Specification DD-G-1403B and the minimum fragment requirement of ANSI Z97.1-1984. The dimensions of the pane are: a = 48 inches, b = 48 inches, and t = 1/2 inch. No blast load will exceed 50 msec.

Find: Maximum blast load capacity of the windows.

Solution: Step 1: Tabulate the design parameters needed to enter Figures 2 to 22.

$a/b = 48/48 = 1.00$

$b = 48$ inches

$t = 1/2$ inch (nominal)

$T = 50$ msec

Step 2: Enter the bottom design graph on Figure 3 and find that the design blast pressure is:

B = 3.85 psi ANS

Problem 2--Design of Tempered Glass Panes

Given: A nonoperable window having a single pane of glass. Glazing: thermally tempered glass meeting Federal Specification DD-G-1403B and the minimum fragment requirements ANSI Z97.1-1984. Dimensions of pane: a = 54 inches, b = 36 inches. Blast loading: B = 4.5 psi, T = 500 msec.

Find: Minimum thickness of glazing required for a probability of failure less than 0.001.

Solution: Step 1: Tabulate the design parameters needed to enter Figures 2 to 22.

a/b = 54/36 = 1.50

b = 36 inches

B = 4.5 psi

T = 500 msec

Step 2: Enter Figures 2 to 22 with the design parameters from Step 1 and find the minimum glazing thickness.

The top graph of Figure 10 applies for the given design parameters. Enter Figure 10 and find the minimum glazing thickness required for B = 4.5 psi and T = 500 msec:

t = 5/8 in. ANS

Problem 3--Design of a Linearly Behaving Pane by the Alternate Design Procedure

Given: A fixed window with a single pane. Glazing is thermally tempered glass meeting Federal Specification DD-G-1403B and ANSI Z97.1 - 1984. The dimensions of the pane are: a = 18 inches, b = 18 inches, and t = 3/4 inch (nominal). Blast loading: B = 45 psi, T = 10 msec

Find: The blast overpressure capacity of the glass pane.

Solution: Step 1: Tabulate the needed parameters.

a/b = 18/18 = 1.00

b = 18 inches

t = 0.719 inch (actual thickness from Table 2)

Step 2: Determine if the pane will behave as a linearly behaving plate under the design loading. Calculate:

b/t = 18/0.719 = 25.0

Enter Table 3 and note the maximum b/t ratio permitted for a pane responding as a linear responding plate to small deflection plate theory is 53.6. The trial pane qualifies; note this pane size is also to the left and above the stepped line in Table 1.

Step 3: Using Equation 1a, and coefficient C_r from Table 3, compute both the static design resistance, r_u, and the effective static design resistance, r_{eff}, as:

$$r_{eff} = r_u = C_r\ (t/b)^2 = 5.79 \times 10^4\ (0.719/18)^2 = 92.4 \text{ psi}$$

The alternate design procedure will give slightly higher values than Table 1 (91.6) due to slight approximations in the derivation of its plate equations.

Step 4: Calculate the natural period of vibration of the pane by Equation 2 and coefficient C_T from Table 3:

$$T_n = C_T\ (b^2/t) = 5.21 \times 10^{-3}\ (18^2/0.719) = 2.35 \text{ msec}$$

Step 5: Calculate the ratio of the effective blast duration, T, to the natural period of vibration of the glass pane T_n:

$$T/T_n = 10.0/2.35 = 4.25$$

Enter the dynamic response chart on Figure 25(a) (Identical with Figure 3-49 of draft Volume III of NAVFAC P-397). Read the Dynamic Load Factor, D_{LF}:

$$D_{LF} = 1.87$$

Step 6: Calculate the blast overpressure capacity of the glass pane according to Equation 9:

$$B = r_{eff}/D_{LF} = 92.4/1.87 = 49.4 \text{ psi}$$ ANS

This is very close to the blast capacity reported in the blast capacity chart (Table 4 - bottom)

Problem 4--Evaluation of Blast Capacity for Tempered Glass by Alternate Design Method

Given: A tempered glass pane. Dimensions of the pane are: a = 36 inches, b = 36 inches, and t = 1/4 inch. The threat blast load has a duration of 5 msec.

Find: Maximum blast capacity.

Solution: Step 1: Compute the aspect ratio, a/b, and determine if the pane will behave as a linearly responding pane under its design load by computing the ratio of the short side of the pane, b, to its actual (not nominal) thickness:

$a/b = 36/36 = 1.00$

$t = 0.219$ inches (from Table 2)

$b/t = 36/0.219 = 164$

As the b/t ratio exceeds 53.6, the pane will behave as a plate responding according to large deflection plate theory. Equations 3 through 9 must be used.

Step 2: Calculate the nondimensional design stress, S_{ND}, according to Equation 3:

$$S_{ND} = 0.0183\ (b/t)^2 = 0.0183\ (36/0.219)^2 = 495$$

Step 3: Enter Figure 23 with $S_{ND} = 495$ and $a/b = 1.00$, and read the nondimensional design load, L_{ND}.

$$L_{ND} = 3400$$

Step 4: Calculate the static design resistance, r_u, according to Equation 4 as:

$$r_u = 876{,}000\ (L_{ND})\ (t/b)^4 = 876{,}000\ (3400)\ (0.219/36)^4 = 4.08 \text{ psi}$$

The value of r_u in Table 1 is 4.04 psi.

Step 5: Enter Figure 24 with $a/b = 1.00$ and $L_{ND} = 3400$, and record the nondimensional deflection X/t.

$$X/t = 4.1$$

The design center deflection of the glass pane is calculated according to Equation 5 as:

$$X_u = (X/t)t = (4.1)(0.219) = 0.898 \text{ inch}$$

Step 6: Calculate the effective static elastic resistance, r_{eff}, of an equivalent linearly responding pane according to Equation 6:

$$r_{eff} = 0.4\ (r_1 + r_2 + r_3 + r_4 + 0.r_5)$$

A table is often convenient for the calculation.

Effective Static Elastic Resistance Work Table

Center Deflection	Center Deflection X (in)	Nondimensional Deflection X/t	Nondimensional Design Load L_{ND}	Static Load r (psi)	Equation 6 Designation
$0.2\ X_u$	0.180	0.820	260	0.312	r_1
$0.4\ X_u$	0.359	1.64	590	0.708	r_2
$0.6\ X_u$	0.539	2.46	1250	1.50	r_3
$0.8\ X_u$	0.718	3.28	2150	2.58	r_4
X_u	0.898	4.10	3400	4.08	r_u

$$\begin{aligned} r_{eff} &= 0.4\ (0.312 + 0.708\ \ 1.50 + 2.58 + 0.5\ (4.08)) \\ &= 2.86 \text{ psi} \end{aligned}$$

Step 7: Calculate the effective stiffness, K_E, according to Equation 7 as:

$$K_e = r_{eff}/X_u = 2.86/0.898 = 3.18 \text{ psi/in}$$

Step 8: Calculate the fundamental period of vibration of the glazing, T_n, as:

$$T_n = 2\pi\sqrt{\frac{K_{LM}\ m}{K_E}}$$

K_{LM}, the load mass factor of the glass, is:

$$K_{LM} = 0.63 + 0/16\ (a/b - 1) = 0.63 + 0.16\ (1 - 1) = 0.63$$

The unit mass of the glass is computed as:

$$m = 233t = 233\ (0.219) = 51.0$$

With these parameters calculated, T_n, is calculated as:

$$T_n = 2\pi\ \ 0.63\ (51.0)/3.18 = 20.2 \text{ msec}$$

Step 9: Enter the dynamic response chart on Figure 25a (identical to Figure 3-49 of Volume III of NAVFAC P-397 draft) with the ratio of the effective duration of the blast load to the fundamental period of vibration of the glass pane, T/T_n.

$$T/T_n = 5/20.0 = 0.25$$

$$D_{LF} = 0.72$$

Step 10: The blast capacity of the glass pane can be calculated according to Equation 9 as:

$$B = r_{eff}/D_{LF} = 2.86/0.73 = 3.92 \text{ psi} \qquad \underline{\text{ANS}}$$

This is close to the value reported (3.83 psi) in the blast capacity charts (Figure 2 - top).

Problem 5--Design Loads for Window Frame

Given: A nonoperable window has a single pane of glass. The glazing is heat-treated tempered glass meeting Federal Specification DD-G-1403B and ANSI Z97.1-1984. The dimensions of the pane are: a = 37.5 inches, b = 30 inches. Frame width: w = 2 inches. Blast loading: B = 12 psi, T = 1,000 msec.

Find: Thickness of glazing required for a probability of failure equal to or less than 0.001 and design loading for window frame.

Solution: **Step 1**: Tabulate the design parameters needed to enter Figures 2 to 22.

$a/b = 37.5/30 = 1.25$

$b = 30$ inches

$B = 12$ psi

$T = 1{,}000$ msec

Step 2: Select the minimum glazing thickness.

Enter the lower graph of Figure 7, which applies for the given design parameters. The minimum glazing thickness required is:

$t = 3/4$ inch nominal **ANS**

Step 3: Calculate the static ultimate uniform load that produces the same maximum frame load as the blast load.

Enter Table 1 for tempered glass with a pane size of 37.5 by 30 inches, $a/b = 1.25$, and $t = 3/4$ inch, and find the static uniform design load capacity of the glazing to be:

$r_u = 24.6$ psi

Thus, the window frame must be designed to safely support without undue deflection a static uniform load equal to 24.6 psi applied normal to both the glazing and exposed frame members.

Step 4: Calculate the design loading for the window frame.

Enter Table 4 with $a/b = 1.25$, and find by interpolation the design coefficients for the frame loading to be:

$C_R = 0.077$ ANS

$C_x = 0.545$

$C_y = 0.543$

From Equation 12, the concentrated load in each corner of the pane is:

$$R \text{ (corners)} = 0.077\ (24.6)(37.5)^2$$

$$= 2{,}660 \text{ pounds}$$ ANS

From Equation 10, the design loading for the frame in the long direction, a, is:

$$V_x = 0.545\ (24.6)(30) \sin (\pi x/37.5) + 24.6(2)$$

$$V_x = 402 \sin (\pi x/37.5) + 49.2 \text{ lb/in}$$ ANS

From Equation 11, the design loading for the frame in the short direction, b, is:

$$V_y = 0.543\ (24.6)(30) \sin (\pi y/37.5) + 24.6(2)$$

$$V_y = 400 \sin (\pi y/40) + 49.2 \text{ lb/in}$$ ANS

Distribution of the design load of the pane on the frame is shown in Figure 27.

As the fundamental period of vibration of the pane, T_n, is 8.74 msec (from Table 6), the ratio of the effective blast duration to the fundamental period of vibration is:

$$T/T_n = 1{,}000/8.74 = 114$$

As this ratio exceeds ten, rebound can be ignored.

Problem 6--Design Loads for Multipane Frame

Given: A nonoperable window consists of four equal size panes of glass. The glazing is heat-treated tempered glass meeting Federal Specification DD-G-1403B and the minimum size fragment requirements of ANSI Z97.1-1984. Dimensions of the panes: $a = 22.5$ inches, $b = 18$ inches The exposed frame width is 3 inches. Blast loading: $B = 14$ psi, $T = 50$ msec.

Find: Minimum thickness of glazing required for a probability of failure equal to or less than 0.001 and the design loads for the framing system.

Solution: Step 1: Tabulate the design parameters needed to enter Figures 2 to 22.

$a/b = 22.5/18 = 1.25$

$b = 18$ inches

$B = 14$ psi

$T = 50$ msec

Step 2: Select the minimum glazing thickness.

Enter the bottom graph on Figure 6, which applies for the given design parameters. The minimum glazing thickness required is:

$t = 1/2$ inch nominal ANS

Step 3: Calculate the static ultimate uniform load that produces the same maximum reactions on the window frame as the blast load.

Enter Table 1 with $b = 18$ inches, $a/b = 1.25$, and $t = 3/16$ inch, and find the static design uniform load capacity of the glazing to be:

$r_u = 23.1$ psi

The window frame must be designed to safely support without undue deflections a static uniform load equal to 29.1 psi applied perpendicular to the glazing and to the exposed surface of the frame members.

Step 4: Calculate the design loading for the window frame.

Enter Table 4 with a/b = 1.25. With interpolation, the design coefficients for the frame loading are:

$$C_R = 0.077$$

$$C_x = 0.545$$

$$C_y = 0.543$$

From Equation 12, the concentrated loads in the corners of each pane are:

$$R \text{ (corners)} = -0.077\,(29.1)(18)^2 = -726 \text{ pounds}$$ ANS

From Equation 10, the design loading for the long spans of the frame and mullions are:

$$V_x = 0.545\,(29.1)(18) \sin(\pi x/22.5) + 29.1(3)$$

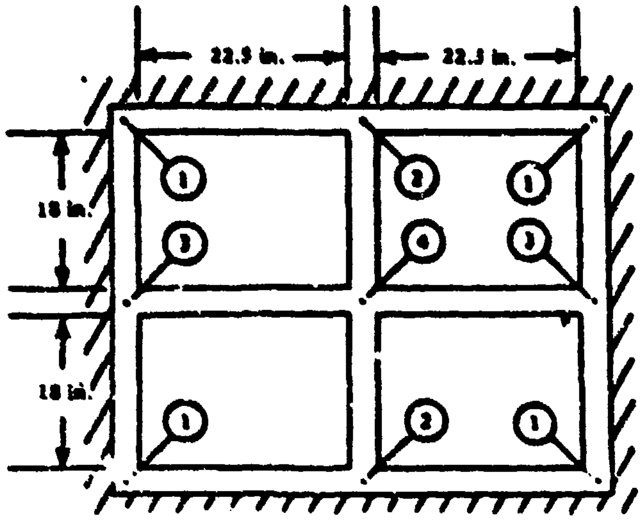
$$= 285 \sin(\pi x/22.5) + 87.3 \text{ lb/in.}$$ ANS

From Equation 11, the design loading for the short spans of the frame and mullions are:

$$V_y = 0.543\,(29.1)(18) \sin(\pi y/18) + 29.1(3)$$

$$= 284 \sin(\pi y/18) + 87.3 \text{ lb/in.}$$ ANS

The design loads for the window frame are shown in the following figure and table.



Locations	Design Load
①	R
② ③	2R
④	4R
①–②	V_x
①–③	V_y
②–④	$2 V_y$
③–④	$2 V_x$

Problem 7--Design Acceptance Based Upon Certification Test Results

Given: A window, 54 x 36 x 3/8-inch with a single pane of tempered glass, is designed to safely resist a blast load, B, of 2.7 psi with an effective blast duration, T, of 200 msec. Certification testing involved testing three window assemblies (n = 3) to failure. Failure loads, $\hat{r}_i$, were recorded at 14.0, 17.0, and 13.7 psi.

Find: Determine if the window design is acceptable based on results from the certification tests.

Solution: Step 1: Tabulate the design parameters needed to enter Table 1:

$b = 36$ inches

$a/b = 54/36 = 1.50$

$t = 3/8$ inch nominal

Step 2: Employing Table 1, select the static design load, r_u, corresponding to the glass pane geometry.

$r_u = 6.90$ psi

Calculate the static load capacity of the tempered glass for certification from Equation 13:

$$r_s = 0.876\ r_u = 6.04\ \text{psi}$$

Step 3: Calculate the arithmetic mean, $\bar{r}$, of all the samples tested.

Using Equation 15:

$$\bar{r} = \frac{\sum_{i=1}^{n} \hat{r}_i}{n} = \frac{(14.0 + 17.0 + 13.7)}{3} = 14.9\ \text{psi}$$

Step 4: Using Equation 16, calculate the sample standard deviation, s:

$$s = \sqrt{\frac{\sum_{i=1}^{n} (\hat{r}_i - \bar{r})^2}{(n-1)}}$$

$$= \sqrt{\frac{(14.0-14.9)^2 + (17.0-14.9)^2 + (13.7-14.9)^2}{(3-1)}}$$

$$= 1.82\ \text{psi}$$

Step 5: Verify that the sample standard deviation, s, is larger than the minimum value, s_{min}, prescribed in Equation 17.

$$s = 1.82\ \text{psi} > s_{min}$$

$$= 0.145\ r_s$$

$$= 0.145\ (6.04)$$

$$= 0.876\ \text{psi}$$

Thus, s = 1.82 psi is the appropriate value to use in subsequent calculations.

Step 6: Using Table 5, select the acceptance coefficient, α, that correlates with the three samples tested.

Entering Table 5, with $n = 3$, find:

$$\alpha = 3.05$$

Step 7: Verify that the window and frame passed the certification tests by meeting the conditions of Equation 14:

$$\begin{aligned} \bar{r} &= 14.9 \text{ psi} \geq r_s + s\,\alpha \\ &= 6.04 + 1.82\,(3.05) \\ &= 11.6 \text{ psi} \end{aligned}$$

Therefore, the window assembly design is considered safe for the prescribed blast loading.

Problem 8--Design Rejection Based Upon Certification Test Results

Given: A window, 30 x 30 x 1/4-inch with a single pane of tempered glass, is designed to safely resist a blast load, B, of 4.0 psi with an effective blast duration, T, of 200 msec. Certification testing involved testing three window assemblies ($n = 3$) to failure. Failure loads, $\hat{r}_i$, were 6.39, 7.49, and 8.47 psi.

Find: Determine if the window design is acceptable based upon results from the certification tests.

Solution: Step 1: Tabulate the design parameters needed to enter Table 1.

$$b = 30 \text{ inches}$$

$$a/b = 30/30 = 1.00$$

$$t = 1/4 \text{ inch}$$

Step 2: Employing Table 1 select the static design load, r_u, corresponding to the pane geometry.

$$r_u = 5.53 \text{ psi}$$

The static load capacity of tempered glass for certification testing, r_s, is calculated according to Equation 13 as:

$$r_s = 0.876\, r_u = 4.84 \text{ psi}$$

Step 3: Calculate the arithmetic mean, $\bar{r}$, of all the samples tested using Equation 15:

$$\bar{r} = \frac{\sum_{i=1}^{n} \hat{r}_i}{n} = \frac{(6.39 + 7.49 \quad 8.47)}{3} = 7.45 \text{ psi}$$

Step 4: Employing Equation 16, calculate the sample standard deviation, s.

The sample standard deviation, s, is calculated as:

$$s = \sqrt{\frac{\sum_{i=1}^{n} (\hat{r}_i - \bar{r})^2}{(n - 1)}}$$

$$= \sqrt{\frac{(6.39-7.45)^2 + (7.49-7.45)^2 + (8.47-7.45)^2}{(3-1)}}$$

$$= 1.04 \text{ psi}$$

Step 5: Verify that the sample deviation, s, is larger than the minimum value, s_{min}, prescribed in Equation 17.

$$s = 1.04 \text{ psi} > s_{min}$$

$$= 0.145\, r_s$$

$= 0.145\ (4.84)$

$= 0.702$ psi

Thus, $s = 1.04$ psi is the appropriate value to use in subsequent calculations.

Step 6: Using Table 5, select the acceptance coefficient, α, and the rejection coefficient, β, for $n = 3$. Entering Table 5 with $n = 3$, find,

$\alpha = 3.05$

$\beta = 0.871$

Step 7: Verify if the window and frame passed the certification tests by meeting the conditions of Equation 14:

$$\bar{r} = 7.45 \text{ psi} < r_s + s\,\alpha = 4.84 + 1.04\ (3.05)$$

$$\bar{r} < 8.01 \text{ psi}$$

ANS

Therefore, the window assembly design does not satisfy Equation 16 and is considered unsafe for the prescribed design blast loading.

Step 8: Determine if the window design should be abandoned or if additional testing is justified. From Equation 18:

$$\bar{r} = 7.45 \text{ psi} > r_s + s\,\beta = 4.84 + 1.04\ (0.871) = 5.75 \text{ psi}$$

Therefore, with a level of confidence of 90%, additional testing may lead to acceptance of the window design. More samples may be tested.

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LIST OF SYMBOLS

a	Long dimension of glass pane, in
B	Peak blast overpressure capacity, psi
b	Short dimension of glass pane, in
C_D	Coefficient for predictions design center deflections, X_u, of linearly behaving panes
C_r	Coefficient for prediction effective design resistance, r_{eff}, of a linearly behaving pane
C_T	Coefficient for prediction fundamental period of vibration, T, of a linearly behaving pane
C_x, C_y	Shear coefficient for load passed from glass pane to its support frame
C_R	Uplifting corner force coefficient passed from glass pane to its support frame
D	Modulus of rigidity of glass pane, in-lb
D_{LF}	Dynamic load factor
E	Modulus of elasticity, psi
f_u	Design stress and allowable principal tensile stress in glass pane for a probability of failure equal to or less than one per thousand, psi
f_y	Yield stress of frame members and fasteners, psi
I	Moment of inertia of window frame, in^4
K_E	Effective stiffness, psi/in
K_{LM}	Load mass factor of the glass pane
n	Number of window assemblies tested
m	Mass ($lb\text{-}ms^2/in$)
P	Blast overpressure at any time, psi
$P(F)$	Probability of failure of glass pane
R	Uplifting nodal force applied by glass pane to corners of frame, lb

r	Resistance, psi
$\tilde{r}$	Test load at failure of frame or glass during certification tests, psi
$\bar{r}$	Mean failure load of n samples, psi
r_{eff}	Effective resistance, psi
r_s	Static load capacity of tempered glass for certification testing, psi
r_u	Design static load capacity of the glass pane, psi
$\bar{r}_u$	Uniform static negative load capacity of the window assembly, psi
s	Sample standard deviation, psi
S_{min}	Minimum value of sample standard deviation accepted in Acceptance Test Specification
T	Effective duration of blast load, msec
T_n	Natural period of vibration of the glass pane, msec
t	Nominal thickness of glass pane, in; elapsed time, msec
V_x	Static load applied by glass pane to long edge of frame, lb/in
V_y	Static load applied by glass pane to short edge of frame, lb/in
w	Width of exposed surface of window frame, in
x	Distance from corner measured along long edge of glass pane, in
X	Center deflection of pane, in
X_u	Center deflection of pane at r_u, in
α	Acceptance coefficient
β	Rejection coefficient
ν	Poisson's ratio

Table 1. Static Design Strength, r_u (psi), for Tempered Glass*

[a = long dimension of glass pane (in.); b = short dimension of glass pane (in.)]

ASPECT RATIO = 1.00

Glass Size, b x a (in.)	Static Design Strength (psi) for a Window thickness, t, of --					
	3/4 in.	5/8 in.	1/2 in.	3/8 in.	5/16 in.	1/4 in.
12x12	206	141	87.7	50.3	27.5	20.2
13x13	176	120	74.7	42.8	23.9	17.6
14x14	151	103	64.5	36.9	21.1	15.5
15x15	132	90.1	56.1	32.4	18.7	14.2
16x16	126	79.2	49.3	28.3	16.7	13.4
17x17	103	70.1	43.7	25.3	15.1	12.7
18x18	91.6	62.5	39.0	23.1	14.1	12.6
19x19	82.2	56.1	35.0	21.0	13.5	12.1
20x20	74.2	50.7	31.6	19.2	12.9	11.0
21x21	67.3	46.0	28.6	17.7	12.7	10.0
22x22	61.3	41.9	26.4	16.3	12.6	9.20
23x23	56.1	38.3	24.4	15.1	11.8	8.52
24x24	[illegible]	35.2	22.7	14.3	10.9	7.91
25x25	47.5	32.4	21.2	13.8	10.1	7.43
26x26	43.5	30.0	19.7	13.4	9.39	7.00
27x27	40.7	27.9	18.5	12.9	8.80	6.62
28x28	37.9	26.2	17.4	12.8	8.26	6.22
29x29	35.3	24.6	16.4	12.6	7.78	5.86
30x30	33.0	23.2	15.4	12.6	7.39	5.53
31x31	30.9	21.9	14.6	12.0	7.04	5.22
32x32	29.0	20.8	14.2	11.3	6.71	4.94
33x33	27.4	19.7	13.8	10.6	6.39	4.69
34x34	26.0	18.7	13.5	10.0	6.07	4.45
35x35	24.8	17.8	13.2	9.50	5.77	4.23
36x36	23.6	17.0	12.8	9.05	5.50	4.04
37x37	22.5	16.1	12.7	8.63	5.24	3.86
38x38	21.5	15.4	12.7	8.24	5.01	3.69
39x39	20.5	14.8	12.6	7.88	4.79	3.53
40x40	19.7	14.4	12.5	7.57	4.58	3.39
41x41	18.8	14.1	11.9	7.30	4.39	3.25
42x42	18.1	13.8	11.4	7.04	4.21	3.12
43x43	17.3	13.5	10.9	6.80	4.05	3.00
44x44	16.7	13.2	10.4	6.56	3.90	2.89
45x45	16.0	13.0	9.99	6.32	3.75	2.78
46x46	15.4	12.9	9.59	6.08	3.62	2.68
47x47	14.9	12.8	9.24	5.86	3.49	2.58
48x48	14.5	12.7	8.91	5.65	3.37	2.49
49x49	14.2	12.6	8.59	5.45	3.25	2.41
50x50	14.0	12.6	8.30	5.27	3.15	2.33
51x51	13.7	12.4	8.02	5.09	3.04	2.25
52x52	13.5	11.9	7.76	4.92	2.95	2.18
53x53	13.3	11.5	7.54	4.76	2.85	2.11
54x54	13.1	11.1	7.33	4.61	2.77	2.05
55x55	12.9	10.7	7.13	4.47	2.68	1.99
56x56	12.8	10.3	6.94	4.33	2.60	1.93
57x57	12.7	9.95	6.76	4.20	2.53	1.87
58x58	12.7	9.66	6.59	4.08	2.45	1.82
59x59	12.6	9.38	6.40	3.97	2.38	1.77
60x60	12.6	9.11	6.22	3.85	2.32	1.72

*Panes to the right and below the stepped dividing line behave according to large deflection plate theory.

(continued)

Table 1. Continued

[a = long dimension of glass pane (in.); b = short dimension of glass pane (in.)]

ASPECT RATIO = 1.25

Glass Size, b x a (in.)	Static Design Strength (psi) for a Window Thickness, t, of --					
	3/4 in.	5/8 in.	1/2 in.	3/8 in.	5/16 in.	1/4 in.
12x15	154	105	65.5	37.5	20.5	15.2
13x16.25	131	89.5	55.8	32.0	17.9	13.5
14x17.5	113	77.2	48.1	27.6	15.8	12.3
15x18.75	98.5	67.2	41.9	24.0	14.2	11.2
16x20	86.6	59.1	36.8	21.1	13.0	10.2
17x21.25	76.7	52.4	32.6	19.0	12.8	9.86
18x22.5	68.4	46.7	29.1	17.2	11.1	9.78
19x23.75	61.4	41.9	26.1	15.8	10.3	9.72
20x25	55.4	37.8	23.6	14.6	9.96	9.54
21x26.25	50.3	34.3	21.4	13.6	9.79	8.69
22x27.5	45.8	31.3	19.7	12.8	9.78	7.95
23x28.75	41.9	28.6	18.2	12.0	9.70	7.36
24x30	38.5	26.3	17.0	11.3	9.49	6.75
25x31.25	35.5	24.2	15.9	10.7	8.77	6.27
26x32.5	32.8	23.4	14.9	10.2	8.14	5.83
27x33.75	30.4	20.8	14.1	9.98	7.57	5.45
28x35	28.3	19.5	13.3	9.80	7.07	5.12
29x36.25	26.4	18.4	12.8	9.79	6.63	4.81
30x37.5	24.6	17.4	12.3	9.77	6.23	4.54
31x38.75	23.1	16.4	11.7	9.71	5.87	4.31
32x40	21.7	15.6	11.2	9.65	5.54	4.09
33x41.25	20.4	14.9	10.7	9.22	5.25	3.90
34x42.5	19.4	14.2	10.3	8.71	4.98	3.71
35x43.75	18.5	13.6	10.1	8.24	4.74	3.53
36x45	17.6	13.1	9.93	7.81	4.52	3.36
37x46.25	16.8	12.7	9.80	7.41	4.32	3.20
38x47.5	16.1	12.3	9.79	7.05	4.14	3.06
39x48.75	15.5	11.8	9.78	6.72	3.97	2.92
40x50	14.8	11.4	9.75	6.42	3.82	2.80
41x51.25	14.3	11.0	9.71	6.13	3.66	2.68
42x52.5	13.8	10.6	9.66	5.87	3.51	2.57
43x53.75	13.4	10.3	9.47	5.63	3.37	2.47
44x55	13.0	10.2	9.06	5.40	3.24	2.37
45x56.25	12.6	10.0	8.68	5.19	3.11	2.28
46x57.5	12.3	9.87	8.32	5.00	3.00	2.19
47x58.75	11.9	9.80	7.99	4.81	2.89	2.11
48x60	11.5	9.79	7.67	4.64	2.78	2.03
49x61.25	11.2	9.78	7.37	4.49	2.68	1.96
50x62.5	10.9	9.77	7.11	4.34	2.59	1.89
51x63.75	10.6	9.74	6.85	4.21	2.50	1.83
52x65	10.3	9.70	6.61	4.08	2.42	1.77
53x66.25	10.2	9.67	6.38	3.96	2.34	1.71

*Panes to the right and below the stepped dividing line behave according to large deflection plate theory.

(continued)

Table 1. Continued

[a = long dimension of glass pane (in.); b = short dimension of glass pane (in.)]

ASPECT RATIO = 1.50

Glass Size, b x a (in.)	Static Design Strength (psi) for a Window Thickness, t, of --					
	3/4 in.	5/8 in.	1/2 in.	3/8 in.	5/16 in.	1/4 in.
12x18	123	83.8	52.3	29.9	16.3	11.9
13x19.5	105	71.4	44.5	23.5	13.9	10.5
14x21	90.2	61.6	38.4	22.0	12.3	9.43
15x22.5	78.6	53.6	33.4	19.2	11.1	8.88
16x24	69.1	47.2	29.4	16.8	10.0	8.26
17x25.5	61.2	41.8	26.0	14.9	9.33	8.14
18x27	54.6	37.3	23.2	13.3	8.85	8.02
19x28.5	49.0	33.4	20.8	12.5	8.44	7.90
20x30	44.2	30.2	18.8	11.4	7.83	7.78
21x31.5	40.1	27.4	17.1	10.6	7.81	7.62
22x33	36.5	24.9	15.6	9.86	7.80	7.03
23x34.5	33.4	22.8	14.2	9.32	7.77	6.45
24x36	30.7	21.0	13.1	8.98	7.77	5.95
25x37.5	28.3	19.3	12.4	8.64	7.63	5.50
26x39	26.2	17.9	11.7	8.24	7.39	5.10
27x40.5	24.3	16.6	11.0	7.86	6.69	4.74
28x42	22.6	15.4	10.4	7.85	6.24	4.42
29x43.5	21.0	14.4	9.89	7.85	5.83	4.14
30x45	19.7	13.4	9.42	7.84	5.47	3.88
31x46.5	18.4	12.8	9.16	7.83	5.13	3.64
32x48	17.3	12.2	8.91	7.82	4.83	3.43
33x49.5	16.2	11.6	8.65	7.72	4.55	3.27
34x51	15.3	11.1	8.34	7.62	4.30	3.13
35x52.5	14.4	10.6	8.05	7.28	4.07	3.00
36x54	13.6	10.2	8.02	6.90	3.85	2.87
37x55.5	13.0	9.78	7.99	6.55	3.66	2.74
38x57	12.5	9.42	7.96	6.22	3.47	2.61
39x58.5	12.0	9.21	7.93	5.92	3.33	2.50
40x60	11.6	9.01	7.91	5.64	3.21	2.39
41x61.5	11.2	8.82	7.88	5.38	3.09	2.29
42x63	10.8	8.60	7.85	5.13	2.98	2.19
43x64.5	10.4	8.35	7.77	4.91	2.88	2.10
44x66	10.1	8.12	7.69	4.70	2.77	2.02
45x67.5	9.71	7.90	7.62	4.50	2.66	1.94
46x69	9.42	7.69	7.35	4.31	2.56	1.86
47x70.5	9.25	7.62	7.06	4.14	2.47	1.79
48x72	9.08	7.55	6.78	3.97	2.38	1.73

*Panes to the right and below the stepped dividing line behave according to large deflection plate theory.

(continued)

Table 1. Continued

[a = long dimension of glass pane (in.); b = short dimension of glass pane (in.)]

ASPECT RATIO = 1.75

Glass Size, b x a (in.)	Static Design Strength (psi) for a Window Thickness, t, of --					
	3/4 in.	5/8 in.	1/2 in.	3/8 in.	5/16 in.	1/4 in.
12x21	109	74.2	46.3	26.5	14.4	10.2
13x22.75	92.6	63.2	39.4	22.6	12.3	8.91
14x24.5	79.9	54.5	34.0	19.5	10.6	8.01
15x26.25	69.6	47.5	29.6	17.0	9.46	7.32
16x28	61.2	41.7	26.0	14.9	8.52	6.83
17x29.75	54.2	37.0	23.0	13.2	7.85	6.36
18x31.5	48.3	33.0	20.6	11.8	7.30	5.93
19x33.25	43.4	29.6	18.5	10.6	6.88	5.76
20x35	39.1	26.7	16.7	9.71	6.49	5.73
21x36.75	35.5	24.2	15.1	8.96	6.12	5.70
22x38.5	32.4	22.1	13.8	8.36	5.84	5.68
23x40.25	29.6	20.2	12.6	7.87	5.73	5.57
24x42	27.2	18.6	11.6	7.43	5.71	5.27
25x43.75	25.1	17.1	10.7	7.11	5.70	5.00
26x45.5	23.2	15.8	9.97	6.81	5.69	4.67
27x47.25	21.5	14.7	9.37	6.52	5.66	4.35
28x49	20.0	13.6	8.83	6.24	5.45	4.05
29x50.75	18.6	12.7	8.38	5.98	5.21	3.79
30x52.5	17.4	11.9	8.01	5.82	4.98	3.56
31x54.25	16.3	11.1	7.66	5.74	4.70	3.36
32x56	15.3	10.4	7.35	5.73	4.43	3.17
33x57.75	14.4	9.93	7.11	5.71	4.17	3.00
34x59.5	13.5	9.46	6.89	5.70	3.94	2.85
35x61.25	12.8	9.02	6.67	5.69	3.73	2.72
36x63	12.1	8.62	6.45	5.67	3.54	2.60
37x64.75	11.4	8.30	6.24	5.63	3.37	2.49
38x66.5	10.8	8.00	6.04	5.44	3.21	2.37
39x68.25	10.3	7.73	5.87	5.26	3.06	2.26
40x70	9.91	7.47	5.80	5.09	2.93	2.16
41x71.75	9.52	7.26	5.74	4.93	2.82	2.06
42x73.5	9.15	7.07	5.72	4.71	2.71	1.97
43x75.25	8.81	6.90	5.70	4.50	2.61	1.89
44x77	8.50	6.73	5.69	4.30	2.51	1.81
45x78.75	8.24	6.55	5.70	4.12	2.42	1.74

*Panes to the right and below the stepped dividing line behave according to large deflection plate theory.

(continued)

Table 1. Continued

[a = long dimension of glass pane (in.); b = short dimension of glass pane (in.)]

ASPECT RATIO = 2.00

Glass Size, b x a (in.)	Static Design Strength (psi) for a Window Thickness, t, of --					
	3/4 in.	5/8 in.	1/2 in.	3/8 in.	5/16 in.	1/4 in.
12x24	97.6	66.6	41.5	23.8	13.0	9.05
13x26	83.1	56.7	35.4	20.3	11.0	7.81
14x28	71.7	48.9	30.5	17.5	9.52	6.87
15x30	62.6	42.6	26.6	15.2	8.31	6.29
16x32	54.9	37.5	23.4	13.3	7.43	5.82
17x34	48.6	33.2	20.7	11.9	6.72	5.40
18x36	43.4	29.6	18.5	10.6	6.26	5.03
19x38	38.9	26.5	16.6	9.49	5.86	4.71
20x40	35.1	24.0	14.9	8.56	5.51	4.56
21x42	31.9	21.7	13.6	7.85	5.19	4.46
22x44	29.0	19.8	12.4	7.25	4.90	4.42
23x46	26.6	18.1	11.3	6.73	4.64	4.39
24x48	24.4	16.6	10.4	6.39	4.55	4.37
25x50	22.5	15.3	9.56	6.08	4.47	4.32
26x52	20.8	14.2	8.84	5.79	4.40	4.24
27x54	19.3	13.2	8.23	5.53	4.39	4.01
28x56	17.9	12.2	7.73	5.29	4.38	3.74
29x58	16.7	11.4	7.27	5.07	4.37	3.50
30x60	15.6	10.7	6.86	4.86	4.31	3.28
31x62	14.6	9.98	6.57	4.67	4.25	3.09
32x64	13.7	9.36	6.32	4.58	4.08	2.93
33x66	12.9	8.80	6.08	4.52	3.85	2.78
34x68	12.2	8.31	5.87	4.47	3.64	2.64
35x70	11.5	7.91	5.66	4.41	3.44	2.51
36x72	10.8	7.53	5.47	4.40	3.26	2.39
37x74	10.3	7.18	5.29	4.39	3.11	2.28
38x76	9.73	6.86	5.12	4.38	2.97	2.18
39x78	9.24	6.62	4.96	4.37	2.84	2.08
40x80	8.78	6.42	4.81	4.34	2.72	1.98
41x82	8.37	6.23	4.67	4.30	2.60	1.89
42x84	8.03	6.05	4.60	4.25	2.50	1.80

*Panes to the right and below the stepped dividing line behave according to large deflection plate theory.

(continued)

Table 1. Continued

[a = long dimension of glass pane (in.); b = short dimension of glass pane (in.)]

ASPECT RATIO = 3.00

Glass Size, b x a (in.)	Static Design Strength (psi) for a Window Thickness, t, of --					
	3/4 in.	5/8 in.	1/2 in.	3/8 in.	5/16 in.	1/4 in.
12x36	81.1	55.4	34.5	19.8	10.8	7.53
13x39	69.1	47.2	29.4	16.9	9.18	6.41
14x42	59.6	40.7	25.4	14.5	7.92	5.57
15x45	51.9	35.4	22.1	12.7	6.90	4.94
16x48	45.6	31.2	19.4	11.1	6.06	4.42
17x51	40.4	27.6	17.2	9.86	5.43	3.98
18x54	36.1	24.6	15.3	8.79	4.92	3.61
19x57	32.4	22.1	13.8	7.89	4.48	3.29
20x60	29.2	19.9	12.4	7.12	4.10	3.01
21x63	26.5	18.1	11.3	6.46	3.77	2.80
22x66	24.1	16.3	10.3	5.88	3.48	2.61
23x69	22.1	15.1	9.40	5.44	3.22	2.44
24x72	20.3	13.8	8.63	5.06	3.00	2.29
25x75	18.7	12.8	7.95	4.71	2.82	2.15
26x78	17.3	11.8	7.35	4.40	2.66	2.08
27x81	16.0	10.9	6.82	4.13	2.51	2.01
28x84	14.9	10.2	6.34	3.88	2.38	1.95
29x87	13.9	9.48	5.91	3.65	2.26	1.89
30x90	13.0	8.86	5.56	3.44	2.14	1.83
31x93	12.2	8.30	5.26	3.25	2.08	1.80
32x96	11.4	7.79	4.98	3.08	2.03	1.78
33x99	10.7	7.32	4.72	2.93	1.97	1.76
34x102	10.1	6.90	4.48	2.80	1.92	1.77

[a = long dimension of glass pane (in.); b = short dimension of glass pane (in.)]

ASPECT RATIO = 4.00

Glass Size, b x a (in.)	Static Design Strength (psi) for a Window Thickness, t, of --					
	3/4 in.	5/8 in.	1/2 in.	3/8 in.	5/16 in.	1/4 in.
12x48	75.7	51.7	32.2	18.5	10.1	7.02
13x52	64.5	44.0	27.5	15.7	8.57	5.99
14x56	55.6	38.0	23.7	13.6	7.39	5.16
15x60	48.5	33.1	20.6	11.8	6.43	4.52
16x64	42.6	29.1	18.1	10.4	5.66	3.99
17x68	37.7	25.8	16.1	9.20	5.01	3.56
18x72	33.7	23.0	14.3	8.20	4.49	3.19
19x76	30.2	20.6	12.9	7.36	4.05	2.87
20x80	27.3	18.6	11.5	6.65	3.67	2.60
21x84	24.7	16.9	10.5	6.03	3.34	2.37
22x88	22.5	15.4	9.59	5.49	3.06	2.18
23x92	20.6	14.1	8.77	5.03	2.81	2.02
24x96	18.9	12.9	8.05	4.63	2.59	1.88
25x100	17.5	11.9	7.42	4.28	2.39	1.76
26x104	16.1	11.0	6.86	3.97	2.23	1.66
27x108	15.0	10.2	6.36	3.70	2.09	1.57
28x112	13.9	9.49	5.92	3.45	1.96	1.49
29x116	13.0	8.85	5.52	3.22	1.84	1.41
30x120	12.1	8.27	5.15	3.02	1.75	1.34

*Panes to the right and below the stepped dividing line behave according to large deflection plate theory.

Table 2. Minimum Design Thicknesses, Clearances, and Bite Requirements

Glass Thickness (Nominal) in	mm	Actual Glass Thickness For Design, t (in)	"A" Minimum Edge Clearance (in)	"B" Nominal Bite (in)	"C" Minimum Face Clearance (in)
5/32	4.0	0.149	3/16	1/2	1/8
3/16	5.0	0.180	3/16	1/2	1/8
1/4	6.0	0.219	1/4	1/2	1/8
3/8	10.0	0.355	5/16	1/2	3/16
1/2	12.0	0.469	3/8	1/2	1/4
5/8	16.0	0.594	3/8	1/2	1/4
3/4	19.0	0.719	3/8	1/2	5/16

Table 3. Maximum (b/t) Ratio for Linear Plate Behavior Under Blast Load and Coefficients for Resistance and Deflection and Fundamental Period of Simply Supported Glass Plates Based on Small Deflection Theory (No Tensile Membrane Behavior)

Aspect Ratio, a/b	Maximum (b/t) Ratio	Design Coefficients		
		Design Resistance, C_r	Design Deflection, C_D	Fundamental Period of Vibration, C_T
1.0	53.6	5.79×10^{4}	2.58×10^{-4}	5.21×10^{-3}
1.2	59.0	4.42×10^{4}	2.72×10^{-4}	6.30×10^{-3}
1.4	63.9	3.68×10^{4}	2.83×10^{-4}	7.21×10^{-3}
1.5	66.2	3.36×10^{4}	2.88×10^{-4}	7.60×10^{-3}
1.6	67.9	3.22×10^{4}	2.91×10^{-4}	7.99×10^{-3}
1.8	71.3	2.91×10^{4}	2.98×10^{-4}	8.65×10^{-3}
2.0	74.7	2.72×10^{4}	3.02×10^{-4}	9.23×10^{-3}
3.0	84.3	2.32×10^{4}	3.12×10^{-4}	10.12×10^{-3}
4.0	89.4	2.24×10^{4}	3.15×10^{-4}	10.36×10^{-3}
∝	89.4	2.24×10^{4}	3.15×10^{-4}	10.44×10^{-3}

Table 4. Coefficients for Frame Loading

a/b	C_R	C_x	C_y
1.00	0.065	0.495	0.495
1.10	0.070	0.516	0.516
1.20	0.074	0.535	0.533
1.30	0.079	0.554	0.551
1.40	0.083	0.570	0.562
1.50	0.085	0.581	0.574
1.60	0.086	0.590	0.583
1.70	0.088	0.600	0.591
1.80	0.090	0.609	0.600
1.90	0.091	0.616	0.607
2.00	0.092	0.623	0.614
3.00	0.093	0.644	0.655
4.00	0.094	0.687	0.685

Table 5. Statistical Acceptance and Rejection Coefficients

Number of Window Assemblies, n	Acceptance Coefficient, α	Rejection Coefficient, β
2	4.14	0.546
3	3.05	0.871
4	2.78	1.14
5	2.65	1.27
6	2.56	1.36
7	2.50	1.42
8	2.46	1.48
9	2.42	1.49
10	2.39	1.52
11	2.37	1.54
12	2.35	1.57
13	2.33	1.58
14	2.32	1.60
15	2.31	1.61
16	2.30	1.62
17	2.28	1.64
18	2.27	1.65
19	2.27	1.65
20	2.26	1.66
21	2.25	1.67
22	2.24	1.68
23	2.24	1.68
24	2.23	1.69
25	2.22	1.70
30	2.19	1.72
40	2.17	1.75
50	2.14	1.77

Table 6. Fundamental Period of Vibration, T_n, for Monolithic Tempered Glass

Aspect Ratio = 1.00

Glass Dimensions (in.)		Fundamental Period of Vibration (msec) for Window Thicknesses, t, of --					
b	a	3/4 in.	5/8 in.	1/2 in.	3/8 in.	3/16 in.	1/4 in.
12	12	1.05	1.27	1.61	2.13	2.83	3.38
13	13	1.23	1.49	1.89	2.50	3.29	3.93
14	14	1.43	1.73	2.19	2.89	3.76	4.50
15	15	1.64	1.99	2.52	3.30	4.39	5.09
16	16	1.87	2.26	2.87	3.72	4.95	5.68
17	17	2.11	2.55	3.23	4.17	5.53	6.27
18	18	2.37	2.86	3.63	4.63	6.12	6.84
19	19	2.64	3.19	4.02	5.10	6.71	7.42
20	20	2.92	3.54	4.43	5.77	7.30	8.08
21	21	3.22	3.90	4.86	6.32	7.89	8.76
22	22	3.53	4.28	5.30	6.89	8.44	9.45
23	23	3.86	4.68	5.75	7.48	9.06	10.2
24	24	4.21	5.07	6.23	8.07	9.72	10.9
25	25	4.56	5.47	6.70	8.65	10.4	11.6
26	26	4.94	5.89	7.40	9.25	11.1	12.3
27	27	5.32	6.33	7.94	9.84	11.8	13.1
28	28	5.72	6.77	8.50	10.4	12.5	13.8
29	29	6.12	7.23	9.07	11.0	13.2	14.6
30	30	6.52	7.70	9.65	11.5	14.0	15.3
31	31	6.93	8.17	10.3	12.2	14.7	16.1
32	32	7.36	8.64	10.8	12.8	15.4	16.9
33	33	7.80	9.41	11.4	13.5	16.1	17.8
34	34	8.24	9.95	12.0	14.2	16.9	18.6
35	35	8.70	10.5	12.6	14.9	17.7	19.4
36	36	9.17	11.1	13.2	15.6	18.4	20.2
37	37	9.64	11.6	13.8	16.3	19.2	21.0
38	38	10.1	12.2	14.3	17.0	20.0	21.9
39	39	11.0	12.8	14.9	17.7	20.9	22.8
40	40	11.4	13.4	15.5	18.5	21.7	23.6
41	41	12.0	14.0	16.1	19.2	22.5	24.5
42	42	12.5	14.6	16.8	19.9	23.3	25.4
43	43	13.1	15.2	17.4	20.6	24.1	26.3
44	44	13.6	15.8	18.1	21.3	25.0	27.2
45	45	14.2	16.4	18.8	22.1	25.8	28.1
46	46	14.8	16.9	19.5	22.8	26.7	29.0
47	47	15.4	17.5	20.2	23.6	27.5	29.9
48	48	16.0	18.1	20.9	24.4	28.4	30.8
49	49	16.6	18.7	21.6	25.2	29.3	31.7
50	50	17.2	19.2	22.3	26.0	30.2	32.6
51	51	17.7	19.8	23.0	26.8	31.1	33.5
52	52	18.3	20.4	23.8	27.6	32.0	34.4
53	53	19.0	21.1	24.5	28.4	32.9	35.4
54	54	19.5	21.8	25.2	29.2	33.7	36.3
55	55	20.1	22.4	26.0	30.0	34.6	37.3
56	56	20.7	23.1	26.7	30.8	35.5	38.2
57	57	21.3	23.8	27.4	31.6	36.4	39.2
58	58	21.8	24.5	28.1	32.5	37.3	40.1
59	59	22.4	25.2	28.8	33.3	38.2	41.1
60	60	23.0	25.9	29.6	34.1	39.2	42.1

Table 6. Fundamental Period of Vibration, T_n, for Monolithic Tempered Glass (Continued)

Aspect Ratio = 1.25

Glass Dimensions (in.)		Fundamental Period of Vibration (msec) for Window Thicknesses, t, of --					
b	a	3/4 in.	5/8 in.	1/2 in.	3/8 in.	3/16 in.	1/4 in.
12	15	1.40	1.69	2.14	2.83	3.82	4.39
13	16.25	1.64	1.99	2.52	3.32	4.41	5.04
14	17.5	1.90	2.30	2.92	3.85	5.03	5.99
15	18.75	2.18	2.64	3.35	4.42	5.68	6.77
16	20	2.49	3.01	3.81	5.03	6.61	7.57
17	21.25	2.81	3.40	4.30	5.61	7.36	8.34
18	22.5	3.15	3.81	4.82	6.21	8.14	9.08
19	23.75	3.50	4.24	5.37	6.83	8.94	9.82
20	25	3.88	4.70	5.95	7.48	9.72	10.6
21	26.25	4.28	5.18	6.56	8.12	10.5	11.5
22	27.5	4.70	5.69	7.14	9.19	11.2	12.4
23	28.75	5.14	6.22	7.73	9.95	12.0	13.3
24	30	5.59	6.77	8.34	10.7	12.7	14.3
25	31.25	6.07	7.34	8.96	11.5	13.6	15.2
26	32.5	6.56	7.94	9.60	12.3	14.5	16.2
27	33.75	7.08	8.56	10.3	13.1	15.5	17.2
28	35	7.61	9.13	10.9	13.9	16.4	18.2
29	36.25	8.16	9.71	12.1	14.6	17.3	19.2
30	37.5	8.74	10.3	12.9	15.3	18.3	20.2
31	38.75	9.33	11.0	13.6	16.1	19.3	21.2
32	40	9.94	11.6	14.4	16.8	20.3	22.3
33	41.25	10.5	12.2	15.2	17.7	21.3	23.3
34	42.5	11.1	12.9	16.0	18.6	22.3	24.4
35	43.75	11.7	13.5	16.8	19.5	23.3	25.5
36	45	12.3	14.8	17.6	20.4	24.3	26.6
37	46.25	12.9	15.5	18.3	21.3	25.3	27.7
38	47.5	13.5	16.3	19.1	22.3	26.3	28.8
39	48.75	14.2	17.0	19.8	23.2	27.4	29.9
40	50	14.8	17.8	20.5	24.2	28.4	31.0
41	51.25	15.5	18.6	21.3	25.1	29.5	32.2
42	52.5	16.1	19.4	22.0	26.1	30.6	33.4
43	53.75	16.8	20.2	22.8	27.1	31.7	34.6
44	55	18.2	21.0	23.7	28.1	32.8	35.7
45	56.25	18.9	21.8	24.6	29.1	33.9	37.0
46	57.5	19.7	22.5	25.5	30.1	35.0	38.2
47	58.75	20.5	23.3	26.4	31.1	36.2	39.4
48	60	21.2	24.0	27.4	32.1	37.3	40.6
49	61.25	22.0	24.8	28.3	33.1	38.5	41.8
50	62.5	22.8	25.5	29.2	34.1	39.6	43.1
51	63.75	23.6	26.2	30.2	35.2	40.8	44.3
52	65	24.4	27.0	31.1	36.2	42.0	45.6
53	66.25	25.2	27.8	32.1	37.2	43.2	46.8

Table 6. Fundamental Period of Vibration, T_n, for Monolithic Tempered Glass (Continued)

Aspect Ratio = 1.50

Glass Dimensions (in.)		Fundamental Period of Vibration (msec) for Window Thicknesses, t, of --					
b	a	3/4 in.	5/8 in.	1/2 in.	3/8 in.	3/16 in.	1/4 in.
12	18	1.59	1.92	2.43	3.22	4.36	5.09
13	19.5	1.86	2.26	2.86	3.78	5.12	5.83
14	21	2.16	2.62	3.31	4.38	5.84	6.61
15	22.5	2.48	3.00	3.80	5.03	6.56	7.79
16	24	2.82	3.42	4.33	5.72	7.32	8.70
17	25.5	3.19	3.86	4.89	6.46	8.09	9.63
18	27	3.57	4.33	5.48	7.23	9.37	10.5
19	28.5	3.98	4.82	6.10	7.93	10.3	11.3
20	30	4.41	5.34	6.76	8.65	11.2	12.1
21	31.5	4.86	5.89	7.46	9.40	12.1	13.0
22	33	5.34	6.46	8.18	10.2	13.0	14.1
23	34.5	5.83	7.06	8.94	10.9	13.8	15.1
24	36	6.35	7.69	9.71	12.4	14.6	16.2
25	37.5	6.89	8.34	10.4	13.3	15.5	17.3
26	39	7.46	9.02	11.1	14.2	16.5	18.4
27	40.5	8.04	9.73	11.9	15.1	17.6	19.6
28	42	8.65	10.5	12.6	16.0	18.6	20.7
29	43.5	9.28	11.2	13.4	16.9	19.7	21.9
30	45	9.93	12.0	14.2	17.8	20.8	23.1
31	46.5	10.6	12.7	14.9	18.5	21.9	24.3
32	48	11.3	13.4	16.6	19.3	23.1	25.5
33	49.5	12.0	14.1	17.5	20.2	24.2	26.7
34	51	12.8	14.9	18.4	21.1	25.4	27.8
35	52.5	13.5	15.6	19.3	22.1	26.6	29.0
36	54	14.3	16.4	20.2	23.2	27.8	30.3
37	55.5	15.0	17.2	21.2	24.3	28.9	31.5
38	57	15.7	18.0	22.1	25.3	30.2	32.8
39	58.5	16.4	18.7	22.9	26.4	31.3	34.1
40	60	17.2	20.5	23.8	27.5	32.5	35.4
41	61.5	17.9	21.4	24.5	28.6	33.7	36.7
42	63	18.6	22.3	25.3	29.7	34.9	38.1
43	64.5	19.4	23.2	26.2	30.8	36.1	39.4
44	66	20.2	24.2	27.1	32.0	37.4	40.8
45	67.5	21.0	25.1	28.0	33.1	38.7	42.2
46	69	21.7	26.0	29.0	34.3	40.0	43.6
47	70.5	22.4	26.9	30.0	35.5	41.3	45.0
48	72	24.5	27.8	31.1	36.7	42.6	46.4

Table 6. Fundamental Period of Vibration, T_n, for Monolithic Tempered Glass (Continued)

Aspect Ratio = 1.75

Glass Dimensions (in.)		Fundamental Period of Vibration (msec) for Window Thicknesses, t, of --					
b	a	3/4 in.	5/8 in.	1/2 in.	3/8 in.	3/16 in.	1/4 in.
12	21	1.69	2.04	2.59	3.42	4.63	5.52
13	22.75	1.98	2.40	3.04	4.01	5.44	6.37
14	24.5	2.30	2.78	3.52	4.65	6.30	7.27
15	26.25	2.64	3.19	4.04	5.34	7.15	8.20
16	28	3.00	3.63	4.60	6.08	8.02	9.52
17	29.75	3.39	4.10	5.19	6.86	8.93	10.6
18	31.5	3.80	4.60	5.82	7.69	9.85	11.7
19	33.25	4.23	5.12	6.49	8.57	11.2	12.8
20	35	4.69	5.68	7.19	9.41	12.3	13.8
21	36.75	5.17	6.23	7.92	10.3	13.4	14.8
22	38.5	5.67	6.87	8.70	11.2	14.5	15.8
23	40.25	6.20	7.51	9.51	12.1	15.6	16.8
24	42	6.75	8.17	10.4	13.0	16.6	18.0
25	43.75	7.33	8.87	11.2	13.9	17.6	19.1
26	45.5	7.92	9.59	12.1	15.5	18.6	20.3
27	47.25	8.54	10.3	12.9	16.6	19.6	21.6
28	49	9.19	11.1	13.8	17.7	20.7	22.9
29	50.75	9.86	11.9	14.7	18.8	21.8	24.2
30	52.5	10.6	12.8	13.6	19.8	23.0	25.5
31	54.25	11.3	13.6	16.5	20.9	24.2	26.9
32	56	12.0	14.5	17.5	22.0	25.4	28.2
33	57.75	12.8	15.4	18.3	22.9	26.7	29.6
34	59.5	13.6	16.2	20.1	23.9	28.0	30.9
35	61.25	14.4	17.1	21.2	24.9	29.4	32.3
36	63	15.2	17.9	22.3	25.9	30.7	33.6
37	64.75	16.1	18.8	23.3	27.0	32.0	35.0
38	66.5	16.9	19.8	24.4	28.1	33.4	36.5
39	68.25	17.8	20.7	25.5	29.3	34.7	38.0
40	70	18.6	21.6	26.6	30.4	36.1	39.5
41	71.75	19.5	22.5	27.7	31.5	37.4	40.9
42	73.5	20.3	24.4	28.7	32.8	38.8	42.5
43	75.25	21.2	25.4	29.7	34.0	40.2	44.0
44	77	22.1	26.5	30.7	35.3	41.6	45.5
45	78.75	23.0	27.6	31.7	36.6	43.0	47.1

Table 6. Fundamental Period of Vibration, T_n, for Monolithic Tempered Glass (Continued)

Aspect Ratio = 2.00

Glass Dimensions (in.)		Fundamental Period of Vibration (msec) for Window Thicknesses, t, of --					
b	a	3/4 in.	5/8 in.	1/2 in.	3/8 in.	3/16 in.	1/4 in.
12	24	1.78	2.16	2.73	3.61	4.89	5.85
13	26	2.09	2.53	3.21	4.24	5.74	6.82
14	28	2.43	2.94	3.72	4.91	6.66	7.84
15	30	2.78	3.37	4.27	5.64	7.63	8.89
16	32	3.17	3.83	4.86	6.42	8.61	9.96
17	34	3.58	4.33	5.48	7.24	9.64	11.4
18	36	4.01	4.85	6.15	8.12	10.7	12.7
19	38	4.47	5.41	6.85	9.35	11.8	13.9
20	40	4.93	5.99	7.59	10.0	13.3	15.2
21	42	5.46	6.61	8.37	11.09	14.5	16.4
22	44	5.99	7.25	9.18	12.0	15.7	17.6
23	46	6.55	7.92	10.0	13.0	17.0	18.8
24	48	7.13	8.63	10.9	14.1	18.3	19.9
25	50	7.73	9.36	11.9	15.2	19.5	21.1
26	52	8.37	10.1	12.8	16.2	20.7	22.2
27	54	9.02	10.9	13.8	17.9	21.9	23.5
28	56	9.70	11.7	14.8	19.1	23.0	24.9
29	58	10.4	12.6	15.8	20.3	24.1	26.4
30	60	11.1	13.5	16.8	21.6	25.3	27.9
31	62	11.9	14.4	17.8	22.9	26.4	29.3
32	64	12.7	15.3	18.9	24.1	27.7	30.8
33	66	13.5	16.3	20.0	25.3	29.1	32.3
34	68	14.3	17.3	21.17	26.6	30.5	33.8
35	70	15.2	18.3	22.1	27.8	32.0	35.3
36	72	16.0	19.2	24.0	28.9	33.5	36.8
37	74	16.9	20.3	25.2	30.1	35.0	38.4
38	76	17.9	21.3	26.5	31.2	36.5	40.0
39	78	18.8	22.3	27.7	32.4	37.9	41.6
40	80	19.8	23.4	29.0	33.5	39.4	43.2
41	82	20.8	24.5	30.3	34.7	40.9	44.9
42	84	21.7	25.6	31.5	35.8	42.4	46.6

Table 6. Fundamental Period of Vibration, T_n, for Monolithic Tempered Glass (Continued)

Aspect Ratio = 3.00

Glass Dimensions (in.)		Fundamental Period of Vibration (msec) for Window Thicknesses, t, of --					
b	a	3/4 in.	5/8 in.	1/2 in.	3/8 in.	3/16 in.	1/4 in.
12	36	2.02	2.45	3.10	4.10	5.35	6.64
13	39	2.37	2.87	3.64	4.81	6.51	7.79
14	42	2.75	3.33	4.22	5.58	7.55	9.02
15	45	3.16	3.83	4.84	6.40	8.67	10.3
16	48	3.60	4.35	5.51	7.28	9.87	11.6
17	51	4.06	4.91	6.22	8.22	11.1	13.1
18	54	4.55	5.52	6.98	9.22	12.4	14.5
19	57	5.07	6.14	7.77	10.3	13.7	16.4
20	60	5.62	6.82	8.61	11.4	15.1	18.1
21	63	6.19	7.50	9.50	12.6	16.6	19.8
22	66	6.80	8.25	10.4	13.8	18.1	21.6
23	69	7.43	8.99	11.4	15.0	20.1	23.6
24	72	8.09	9.79	12.4	16.3	21.4	25.3
25	75	8.78	10.6	13.5	17.6	23.5	27.2
26	78	9.49	11.5	14.6	19.0	25.3	29.1
27	81	10.2	12.4	15.7	20.4	27.1	31.0
28	84	11.0	13.3	16.9	21.8	28.9	32.9
29	87	11.8	14.3	18.1	23.3	30.8	34.9
30	90	12.6	15.3	19.3	24.8	32.8	36.8
31	93	13.5	16.3	20.6	26.9	34.7	38.7
32	96	14.4	17.4	21.9	28.6	36.5	40.5
33	99	15.3	18.5	23.2	30.3	38.4	42.3
34	102	16.2	19.7	24.6	32.0	40.4	44.1

Table 6. Fundamental Period of Vibration, T_n, for Monolithic Tempered Glass (Continued)

Aspect Ratio = 4.00

Glass Dimensions (in.)		Fundamental Period of Vibration (msec) for Window Thicknesses, t, of --					
b	a	3/4 in.	5/8 in.	1/2 in.	3/8 in.	3/16 in.	1/4 in.
12	48	2.09	2.53	3.21	4.24	5.75	6.87
13	52	2.46	2.97	3.77	4.98	6.74	8.07
14	56	2.85	3.45	4.37	5.77	7.82	9.36
15	60	3.27	3.96	5.02	6.63	8.98	10.7
16	64	3.73	4.51	5.71	7.54	10.2	12.2
17	68	4.20	5.09	6.44	8.51	11.5	13.7
18	72	4.71	5.70	7.22	9.54	12.9	15.3
19	76	5.25	6.35	8.05	10.6	14.3	17.0
20	80	[illegible] 82	7.04	8.92	11.8	15.9	18.9
21	84	6.41	7.76	9.83	13.1	17.4	20.8
22	88	7.04	8.52	10.8	14.3	19.1	22.8
23	92	7.69	9.31	11.8	15.6	20.8	24.8
24	96	8.37	10.1	12.8	16.9	22.8	26.9
25	100	9.09	11.0	13.9	18.3	24.7	29.1
26	104	9.83	11.9	15.1	19.8	26.6	31.5
27	108	10.6	12.8	16.3	21.3	28.6	33.5
28	112	11.4	13.8	17.5	22.9	30.7	35.8
29	116	12.2	14.8	18.8	24.5	32.8	38.2
30	120	13.1	15.8	20.1	26.2	35.0	40.6

Table 7. Effective Elastic Static Resistance, r_{eff}

Aspect Ratio = 1

Glass Dimensions (in.)		Effective Elastic Static Resistance (psi) for Glass Thicknesses, t, of --					
b	a	3/4 in.	5/8 in.	1/2 in.	3/8 in.	5/16 in.	1/4 in.
12	12	206	140	87.7	50.3	27.5	19.1
13	13	175	119	74.7	42.8	23.9	16.3
14	14	151	103	64.5	36.9	21.1	14.2
15	15	131	90.1	56.1	32.2	17.5	12.7
16	16	115	79.2	49.3	28.3	15.5	11.6
17	17	102	70.1	43.7	25.5	13.8	10.7
18	18	91.6	62.5	39.0	23.1	12.6	10.3
19	19	82.2	56.1	35.0	21.0	11.7	9.75
20	20	74.2	50.7	31.6	18.0	11.0	8.76
21	21	67.3	46.0	28.6	16.4	10.4	7.93
22	22	61.3	41.9	26.4	15.1	10.2	7.20
23	23	56.1	38.3	24.4	13.9	9.51	6.57
24	24	51.5	35.2	22.7	12.9	8.71	6.01
25	25	47.5	32.4	21.2	12.2	8.01	5.56
26	26	43.9	23.0	18.6	11.5	7.39	5.19
27	27	40.7	27.9	17.3	11.0	6.83	4.87
28	28	37.9	26.2	16.2	10.5	6.33	4.55
29	29	35.3	24.6	15.1	10.3	5.89	4.25
30	30	33.0	23.2	14.2	10.2	5.53	3.98
31	31	30.9	21.9	13.4	9.61	5.22	3.74
32	32	29.0	20.8	12.8	9.00	4.95	3.52
33	33	27.4	18.5	12.2	8.45	4.68	3.31
34	34	26.0	17.5	11.7	7.95	4.42	3.14
35	35	24.8	16.6	11.3	7.49	4.18	2.98
36	36	23.6	15.7	10.9	7.06	3.96	2.82
37	37	22.5	14.9	10.5	6.67	3.75	2.67
38	38	21.5	14.2	10.4	6.31	3.57	2.54
39	39	19.4	13.5	10.3	5.98	3.39	2.42
40	40	18.5	13.0	10.1	5.70	3.24	2.30
41	41	17.6	12.6	9.59	5.45	3.09	2.19
42	42	16.8	12.1	9.12	5.22	2.96	2.09
43	43	16.1	11.7	8.69	5.02	2.83	2.00
44	44	15.4	11.4	8.29	4.83	2.70	1.92
45	45	14.8	11.1	7.92	4.63	2.59	1.84
46	46	14.2	10.8	7.57	4.43	2.48	1.77
47	47	13.6	10.5	7.24	4.25	2.38	1.70
48	48	13.2	10.4	6.93	4.08	2.29	1.64
49	49	12.8	10.3	6.64	3.92	2.20	1.58
50	50	12.4	10.2	6.37	3.77	2.11	1.52
51	51	12.1	9.96	6.11	3.63	2.04	1.47
52	52	11.7	9.56	5.87	3.50	1.96	1.42
53	53	11.4	9.19	5.67	3.37	1.90	1.38
54	54	11.2	8.84	5.48	3.26	1.83	1.33
55	55	10.9	8.52	5.30	3.15	1.77	1.29
56	56	10.7	8.21	5.14	3.05	1.72	1.25
57	57	10.5	7.92	4.99	2.95	1.66	1.21
58	58	10.4	7.64	4.85	2.85	1.61	1.17
59	59	10.3	7.4	4.70	2.76	1.56	1.14
60	60	10.2	7.1	4.55	2.67	1.52	1.11

Table 7. Effective Elastic Static Resistance, r_{eff} (Continued)

Aspect Ratio = 1.25

Glass Dimensions (in.)		Effective Elastic Static Resistance (psf) for Glass Thicknesses, t, of --					
b	a	3/4 in.	5/8 in.	1/2 in.	3/8 in.	5/16 in.	1/4 in.
12	15	154	105	65.5	37.5	20.5	15.2
13	16.25	131	89.5	55.8	32.0	17.9	13.5
14	17.50	113	77.2	48.1	27.6	15.8	11.0
15	18.75	98.5	67.2	41.9	24.0	14.2	9.84
16	20	86.6	59.1	36.8	21.1	11.9	8.91
17	21.25	76.7	52.4	32.6	19.0	10.8	8.36
18	22.50	68.4	46.7	29.1	17.2	9.79	8.12
19	23.75	61.4	41.9	26.1	15.8	8.99	7.86
20	25	55.4	37.8	23.6	14.6	8.50	7.49
21	26.25	50.3	34.3	21.4	13.6	8.19	6.73
22	27.50	45.8	31.3	19.7	11.6	8.07	6.11
23	28.75	41.9	28.6	18.2	10.8	7.79	5.57
24	30	38.5	26.3	17.0	10.1	7.44	5.09
25	31.25	35.5	24.2	15.9	9.40	6.81	4.68
26	32.50	32.8	22.4	14.9	8.89	6.27	4.31
27	33.75	30.4	20.8	14.1	8.53	5.79	4.00
28	35	28.3	19.5	13.4	8.25	5.37	3.73
29	36.25	26.4	18.4	11.7	8.14	4.99	3.49
30	37.50	24.6	17.4	11.0	8.04	4.65	3.28
31	38.75	23.1	16.4	10.4	7.82	4.34	3.09
32	40	21.7	15.6	9.91	7.62	4.07	2.92
33	41.25	20.4	14.9	9.41	7.21	3.84	2.76
34	42.50	19.4	14.2	8.99	6.75	3.62	2.61
35	43.75	18.5	13.6	8.70	6.35	3.43	2.47
36	45	17.6	12.0	8.45	5.99	3.26	2.34
37	46.25	16.8	11.5	8.25	5.66	3.10	2.22
38	47.50	16.1	11.0	8.16	5.35	2.96	2.12
39	48.75	15.5	10.6	8.09	5.07	2.82	2.01
40	50	14.8	10.1	7.98	4.81	2.69	1.91
41	51.25	14.3	9.72	7.91	4.57	2.57	1.82
42	52.50	13.8	9.34	7.66	4.34	2.45	1.74
43	53.75	13.4	9.01	7.43	4.14	2.34	1.66
44	55	11.8	8.78	7.06	3.96	2.25	1.59
45	56.25	11.4	8.57	6.72	3.79	2.16	1.52
46	57.50	11.0	8.38	6.42	3.63	2.07	1.46
47	58.75	10.6	8.24	6.14	3.49	1.98	1.40
48	60	10.3	8.17	5.88	3.36	1.90	1.34
49	61.25	9.93	8.11	5.63	3.23	1.83	1.29
50	62.50	9.60	8.06	5.39	3.12	1.76	1.25
51	63.75	9.29	7.93	5.18	3.01	1.69	1.20
52	65	9.02	7.80	4.97	2.90	1.63	1.16
53	66.25	8.82	7.68	4.78	2.80	1.57	1.12

Table 7. Effective Elastic Static Resistance, r_{eff} (Continued)

Aspect Ratio = 1.50

Glass Dimensions (in.)		Effective Elastic Static Resistance (psi) for Glass Thicknesses, t, of --					
b	a	3/4 in.	5/8 in.	1/2 in.	3/8 in.	5/16 in.	1/4 in.
12	18	123	83.8	52.3	29.9	16.3	11.9
13	19.50	105	71.4	44.5	25.5	13.9	10.5
14	21	90.2	61.6	38.4	22.0	12.3	9.43
15	22.50	78.6	53.6	33.6	19.2	11.1	7.86
16	24	69.1	47.2	29.4	16.8	10.1	7.16
17	25.50	61.2	41.8	26.0	14.9	9.31	6.56
18	27	54.6	37.3	23.2	13.3	7.83	6.25
19	28.50	49.0	33.4	20.0	12.3	7.24	6.30
20	30	44.2	30.2	18.8	11.4	6.71	6.23
21	31.50	40.1	27.4	17.1	10.6	6.37	5.91
22	33	36.5	24.9	15.6	9.86	6.16	5.36
23	34.50	33.4	22.8	14.23	9.32	6.35	4.86
24	36	30.7	21.0	13.1	7.99	6.21	4.44
25	37.50	28.3	19.3	12.4	7.56	5.94	4.08
26	39	26.2	17.9	11.7	7.13	5.51	3.75
27	40.50	24.3	16.6	11.0	6.75	5.06	3.47
28	42	22.6	15.4	10.4	6.46	4.68	3.21
29	43.50	21.0	14.4	9.89	6.28	4.35	2.99
30	45	19.7	13.4	9.42	6.18	4.05	2.79
31	46.50	18.4	12.8	9.16	6.33	3.78	2.61
32	48	17.3	12.2	7.90	6.32	3.54	2.45
33	49.50	16.2	11.6	7.57	6.11	3.32	2.33
34	51	15.3	11.1	7.24	5.92	3.12	2.21
35	52.50	14.4	10.6	6.94	5.59	2.93	2.10
36	54	13.6	10.2	6.66	5.24	2.77	2.00
37	55.50	13.0	9.78	6.46	4.94	2.62	1.90
38	57	12.5	9.42	6.32	4.67	2.49	1.81
39	58.50	12.0	9.21	6.20	4.42	2.38	1.[illegible]
40	60	11.6	8.03	6.22	4.19	2.28	1.64
41	61.50	11.2	7.78	6.33	3.98	2.18	1.57
42	63	10.8	7.52	6.36	3.78	2.09	1.49
43	64.50	10.4	7.26	6.20	3.60	2.01	1.42
44	66	10.1	7.02	6.05	3.43	1.92	1.36
45	67.50	9.71	6.79	5.91	3.27	1.84	1.30
46	69	9.42	6.57	5.65	3.13	1.77	1.25
47	70.50	9.25	6.45	5.39	2.99	1.70	1.20
48	72	8.12	6.33	5.14	2.86	1.63	1.15

Table 7. Effective Elastic Static Resistance, r_{eff} (Continued)

Aspect Ratio = 1.75

Glass Dimensions (in.)		Effective Elastic Static Resistance (psi) for Glass Thicknesses, t, of --					
b	a	3/4 in.	5/8 in.	1/2 in.	3/8 in.	5/16 in.	1/4 in.
12	21	109	74.2	46.3	26.5	14.4	10.2
13	22.75	92.6	63.2	39.4	22.6	12.3	8.91
14	24.50	7[illegible].9	54.5	34.0	19.5	10.5	8.01
15	26.25	69.6	47.5	29.6	17.0	9.46	7.32
16	28	61.2	41.7	26.0	14.9	8.52	6.20
17	29.75	54.2	37.0	23.1	13.2	7.85	5.65
18	31.50	48.3	33.0	20.6	11.7	7.30	5.19
19	33.25	43.4	29.6	18.5	10.67	6.27	4.89
20	35	39.1	26.7	16.7	9.71	5.79	4.70
21	36.75	35.5	24.2	15.1	8.96	5.38	4.64
22	38.50	32.4	22.1	13.8	8.36	5.05	4.50
23	40.25	29.6	20.2	12.6	7.87	4.84	4.31
24	42	27.2	18.6	11.6	7.43	4.70	4.02
25	43.75	25.1	17.1	10.7	7.11	4.65	3.79
26	45.50	23.2	15.8	9.97	6.17	4.54	3.51
27	47.25	21.5	14.7	9.37	5.82	4.41	3.24
28	49	20.0	13.6	8.83	5.52	4.19	3.00
29	50.75	18.6	12.7	8.38	5.23	3.96	2.78
30	52.50	17.4	11.9	8.01	5.02	3.77	2.60
31	54.25	16.3	11.1	7.66	4.86	3.53	2.43
32	56	15.3	10.4	7.35	4.73	3.30	2.29
33	57.75	14.4	9.93	7.11	4.68	3.09	2.16
34	59.50	13.5	9.46	6.27	4.64	2.90	2.05
35	61.25	12.8	9.02	6.00	4.56	2.73	1.94
36	63	12.1	8.62	5.74	4.46	2.58	1.85
37	64.75	11.4	8.30	5.51	4.36	2.44	1.76
38	66.50	10.8	8.00	5.30	4.18	2.32	1.67
39	68.25	10.3	7.73	5.10	4.01	2.21	1.59
40	70	9.91	7.47	4.97	3.86	2.11	1.51
41	71.75	9.52	7.26	4.85	3.72	2.02	1.44
42	73.50	9.15	6.51	4.75	3.53	1.93	1.38
43	75.25	8.81	6.29	4.70	3.36	1.85	1.32
44	77	8.50	6.07	4.67	3.20	1.78	1.26
45	78.75	8.24	5.86	4.64	3.05	1.71	1.20

Table 7. Effective Elastic Static Resistance, r_{eff} (Continued)

Aspect Ratio = 2.00

Glass Dimensions (in.)		Effective Elastic Static Resistance (psi) for Glass Thicknesses, t, of --					
b	a	3/4 in.	5/8 in.	1/2 in.	3/8 in.	5/16 in.	1/4 in.
12	24	97.6	66.6	41.5	23.8	13.0	9.05
13	26	83.1	56.7	35.4	20.3	11.0	7.81
14	28	71.7	48.9	30.5	17.5	9.52	6.87
15	30	62.4	42.6	26.6	15.2	8.31	6.29
16	32	54.9	37.5	23.4	13.4	7.43	5.81
17	34	48.6	33.2	20.7	11.9	6.72	4.98
18	36	43.4	29.6	18.5	10.6	6.26	4.54
19	38	38.9	26.6	16.6	9.49	5.86	4.19
20	40	35.1	24.0	14.9	8.56	5.12	3.93
21	42	31.9	21.7	13.6	7.85	4.72	3.74
22	44	29.0	19.8	12.4	7.25	4.40	3.59
23	46	26.6	18.1	11.3	6.73	4.11	3.48
24	48	24.4	16.6	10.4	6.39	3.92	3.42
25	50	22.5	15.3	9.56	6.08	3.75	3.33
26	52	20.8	14.2	8.84	5.79	3.62	3.24
27	54	19.3	13.2	8.23	5.15	3.51	3.04
28	56	17.9	12.2	7.73	4.85	3.45	2.81
29	58	16.7	11.4	7.27	4.58	3.40	2.61
30	60	15.6	10.7	6.86	4.36	3.32	2.42
31	62	14.6	9.98	6.57	4.15	3.25	2.27
32	64	13.7	9.36	6.32	3.99	3.10	2.14
33	66	12.9	8.80	6.08	3.86	2.90	2.02
34	68	12.2	8.31	5.87	3.74	2.72	1.91
35	70	11.5	7.91	5.66	3.64	2.56	1.81
36	72	10.8	7.53	5.07	3.56	2.41	1.72
37	74	10.3	7.18	4.84	3.49	2.28	1.63
38	76	9.73	6.86	4.64	3.45	2.17	1.56
39	78	9.24	6.62	4.46	3.41	2.06	1.48
40	80	8.78	6.42	4.30	3.36	1.97	1.41
41	82	8.37	6.23	4.14	3.30	1.88	1.34
42	84	8.03	6.05	4.02	3.25	1.80	1.28

Table 7. Effective Elastic Static Resistance, r_{eff} (Continued)

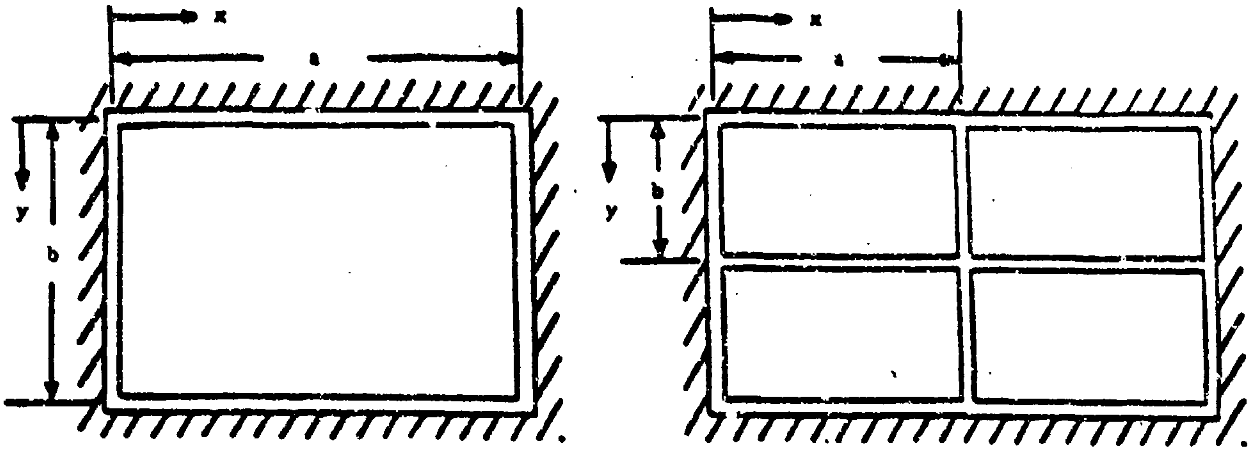
Aspect Ratio = 3.00

Glass Dimensions (in.)		Effective Elastic Static Resistance (psi) for Glass Thicknesses, t, of --					
b	a	3/4 in.	5/8 in.	1/2 in.	3/8 in.	5/16 in.	1/4 in.
12	36	81.1	55.4	34.5	19.8	10.8	7.53
13	39	69.1	47.2	29.4	16.9	9.18	6.41
14	42	59.6	40.7	25.4	14.5	7.92	5.57
15	45	51.9	35.4	22.1	12.7	6.90	4.94
16	48	45.6	31.2	19.4	11.1	6.06	4.42
17	51	40.4	27.6	17.2	9.86	5.43	3.98
18	54	36.1	24.6	15.3	8.79	4.92	3.61
19	57	32.4	22.1	13.8	7.89	4.48	3.15
20	60	29.2	19.9	12.4	7.12	4.10	2.86
21	63	26.5	18.1	11.3	6.46	3.77	2.64
22	66	24.1	16.5	10.3	5.88	3.48	2.45
23	69	22.1	15.1	9.40	5.44	3.08	2.25
24	72	20.3	13.8	8.63	5.06	2.84	2.08
25	75	18.7	12.8	7.95	4.71	2.66	1.92
26	78	17.3	11.8	7.35	4.40	2.49	1.82
27	81	16.0	10.9	6.82	4.13	2.34	1.74
28	84	14.9	10.2	6.34	3.88	2.18	1.66
29	87	13.9	9.48	5.91	3.65	2.04	1.58
30	90	13.0	8.86	5.56	3.44	1.91	1.51
31	93	12.2	8.30	5.26	3.11	1.83	1.47
32	96	11.4	7.79	4.98	2.93	1.76	1.43
33	99	10.7	7.32	4.72	2.78	1.70	1.41
34	102	10.1	6.90	4.48	2.64	1.63	1.39

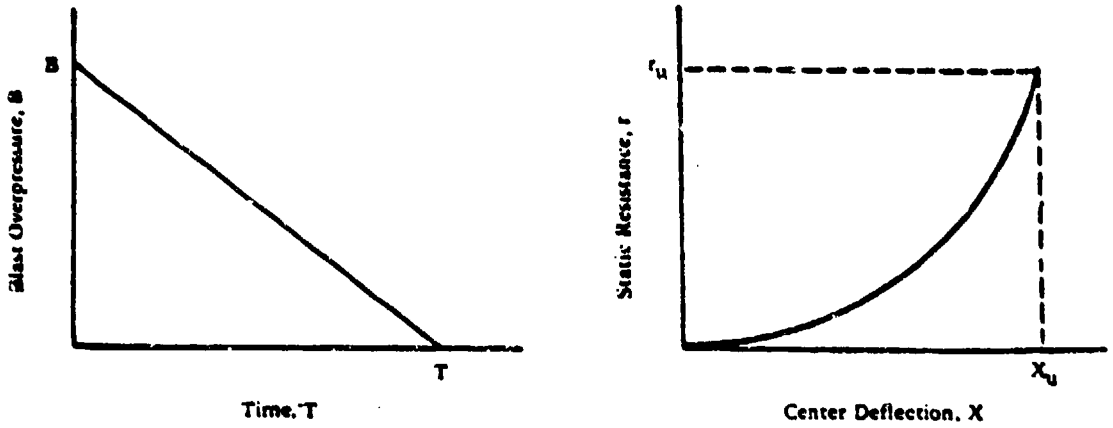
Table 7. Effective Elastic Static Resistance, r_{eff} (Continued)

Aspect Ratio = 4.00

Glass Dimensions (in.)		Effective Elastic Static Resistance (psi) for Glass Thicknesses, t, of --					
b	a	3/4 in.	5/8 in.	1/2 in.	3/8 in.	5/16 in.	1/4 in.
12	48	75.7	51.7	32.2	18.5	10.1	7.02
13	52	64.5	44.0	27.5	15.7	8.57	5.99
14	56	55.6	38.0	23.7	13.6	7.39	5.16
15	60	48.5	33.1	20.6	11.8	6.43	4.52
16	64	42.6	29.1	18.1	10.4	5.66	3.99
17	68	37.7	25.8	16.1	9.20	5.01	3.56
18	72	33.7	23.0	14.3	8.20	4.49	3.19
19	76	30.2	20.6	12.9	7.36	4.05	2.87
20	80	27.3	18.6	11.6	6.65	3.67	2.54
21	84	24.7	16.9	10.5	6.03	3.34	2.30
22	88	22.5	15.4	9.59	5.49	3.06	2.10
23	92	20.6	14.1	8.77	5.03	2.81	1.94
24	96	18.9	12.9	8.05	4.63	2.52	1.79
25	100	17.5	11.9	7.42	4.28	2.32	1.67
26	104	16.1	11.0	6.86	3.97	2.15	1.56
27	108	15.0	10.2	6.36	3.70	2.00	1.46
28	112	13.9	9.49	5.92	3.45	1.88	1.38
29	116	13.0	8.85	5.52	3.22	1.76	1.30
30	120	12.1	8.27	5.15	3.02	1.66	1.23

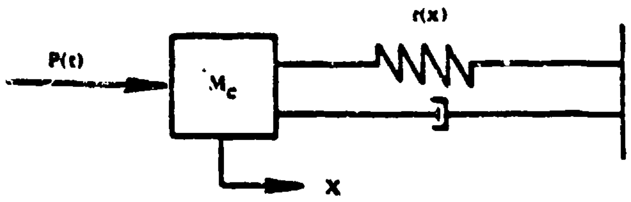


(a) Window pane geometry



(b) Blast loading

(c) Resistance of glass pane



(d) Dynamic response model

Figure 1. Characteristic parameters for glass pane, blast loading, resistance function and response model.

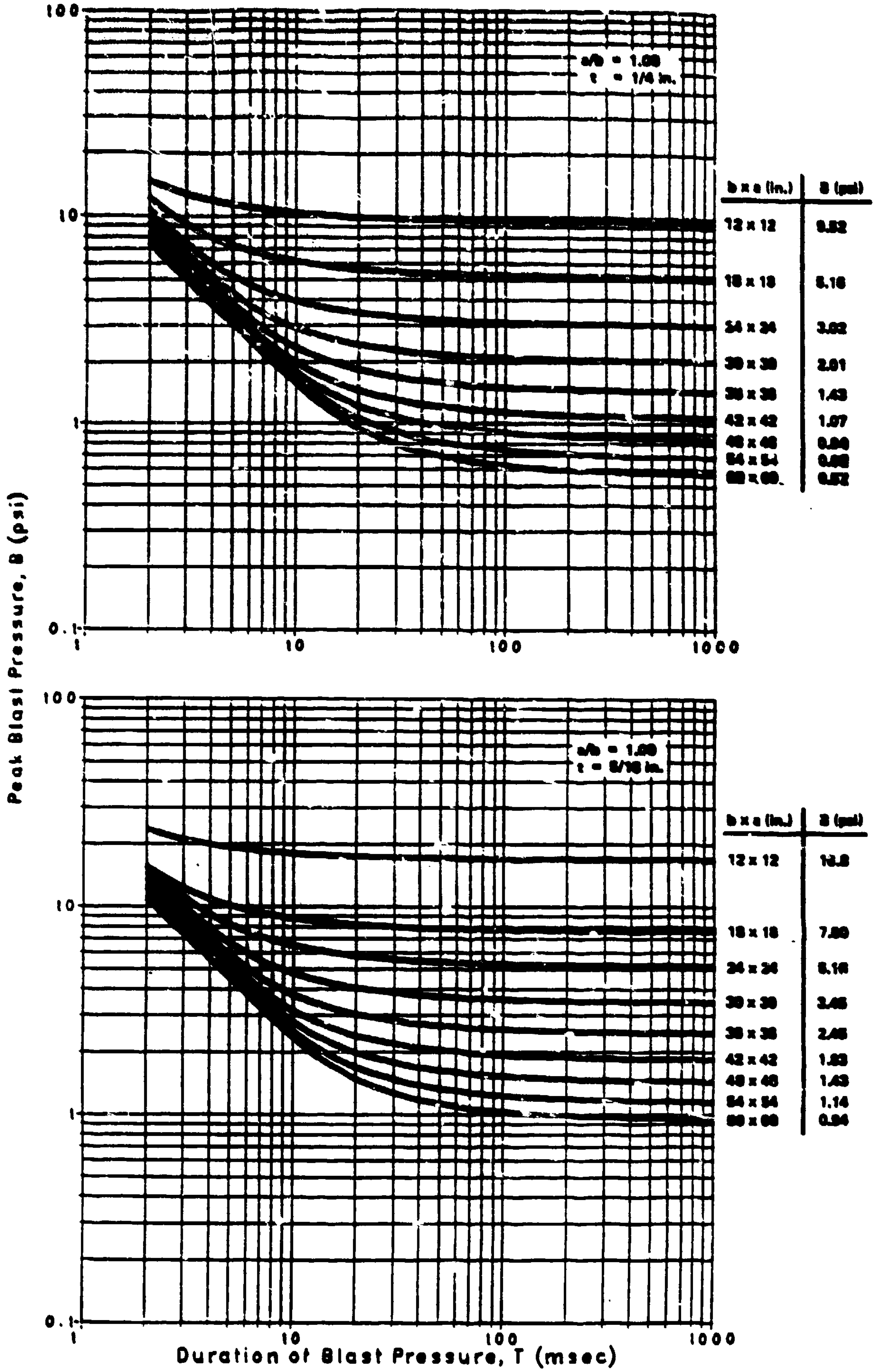


Figure 2. Peak blast pressure capacity for tempered glass panes: a/b = 1.00, t = 1/4 and 5/16 in.

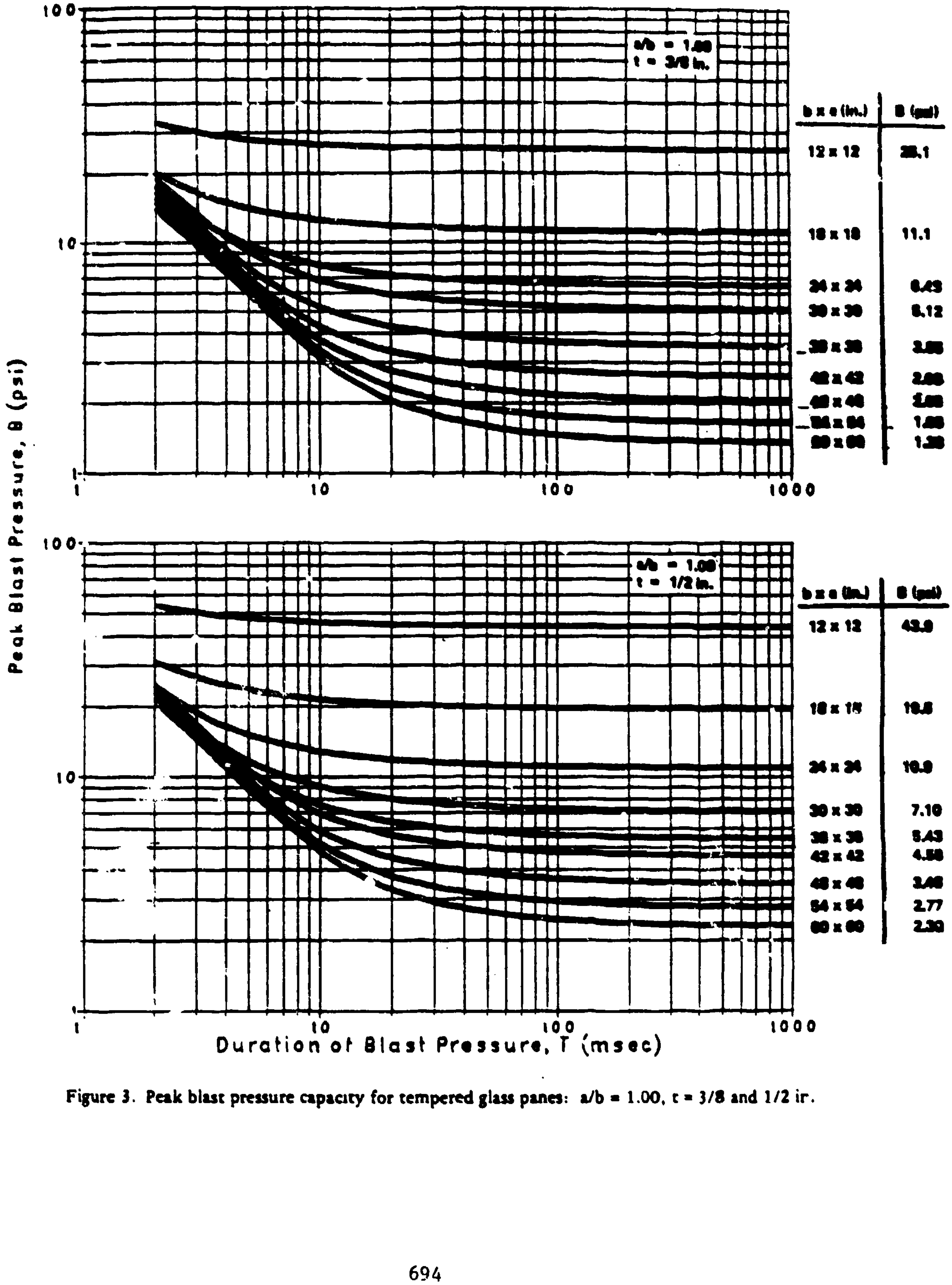


Figure 3. Peak blast pressure capacity for tempered glass panes: a/b = 1.00, t = 3/8 and 1/2 in.

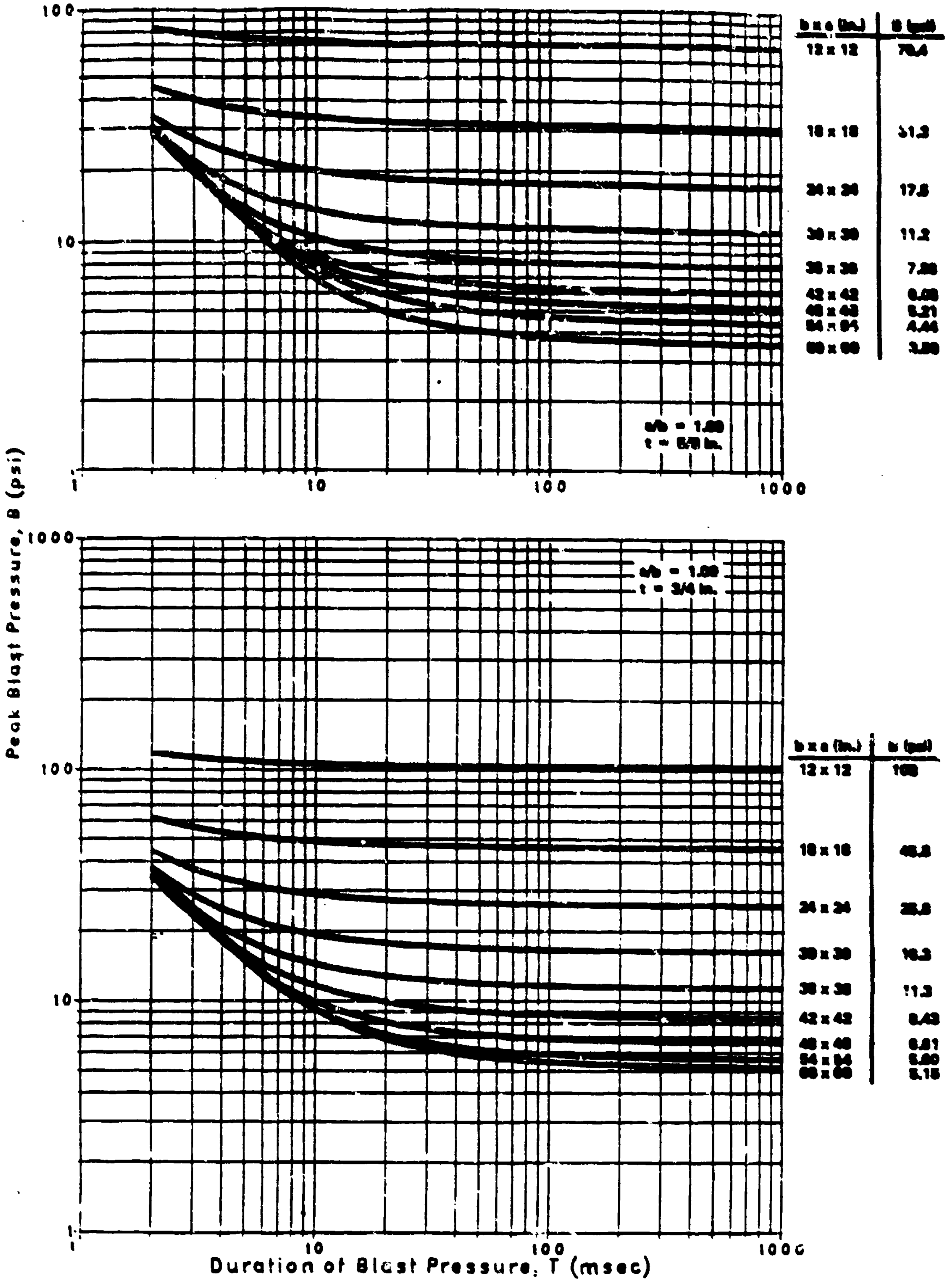


Figure 4. Peak blast pressure capacity for tempered glass panes: a/b = 1.00, t = 5/8 and 3/4 in.

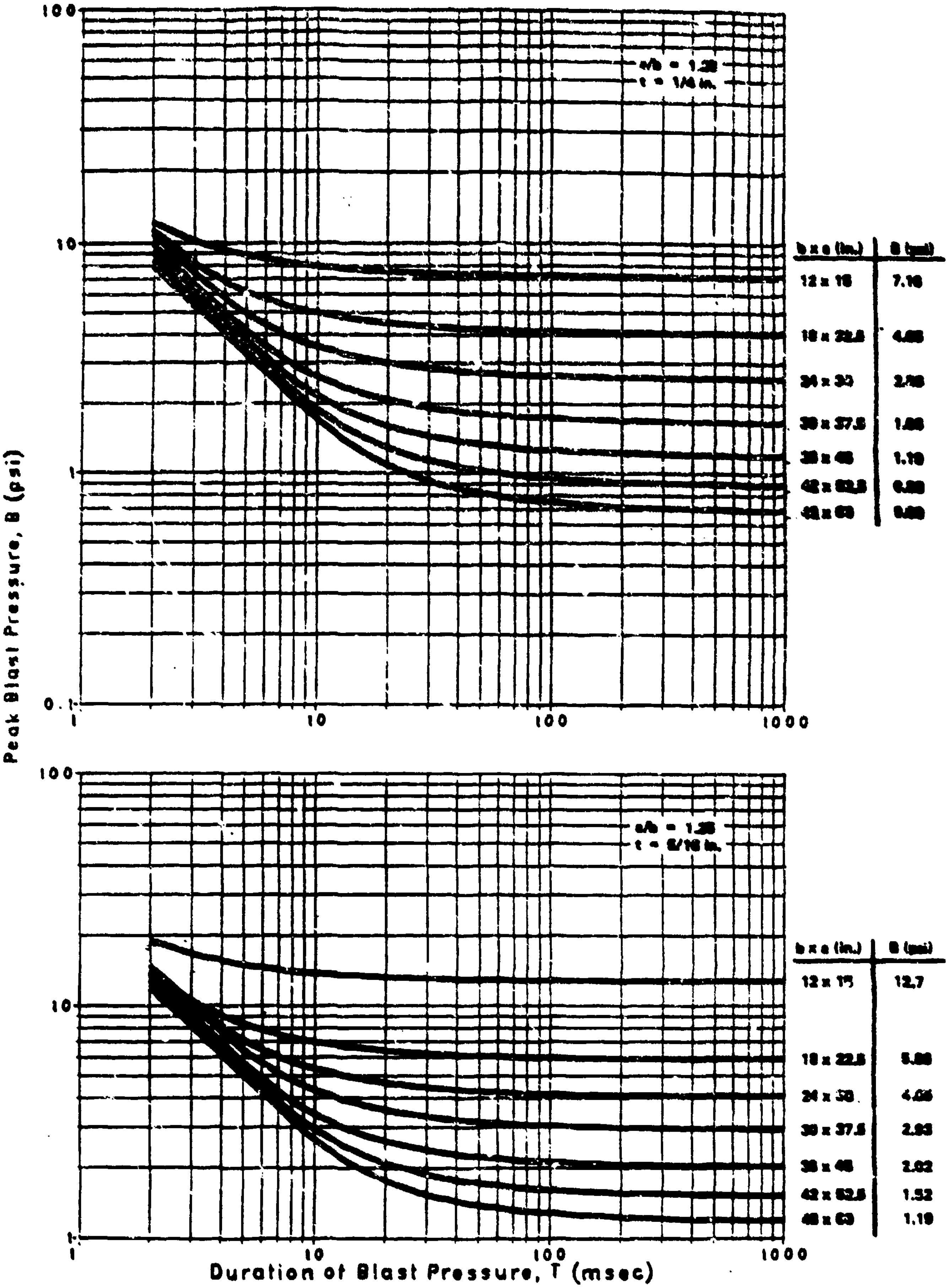


Figure 5. Peak blast pressure capacity for tempered glass panes: a/b = 1.25, t = 1/4 and 5/16 in.

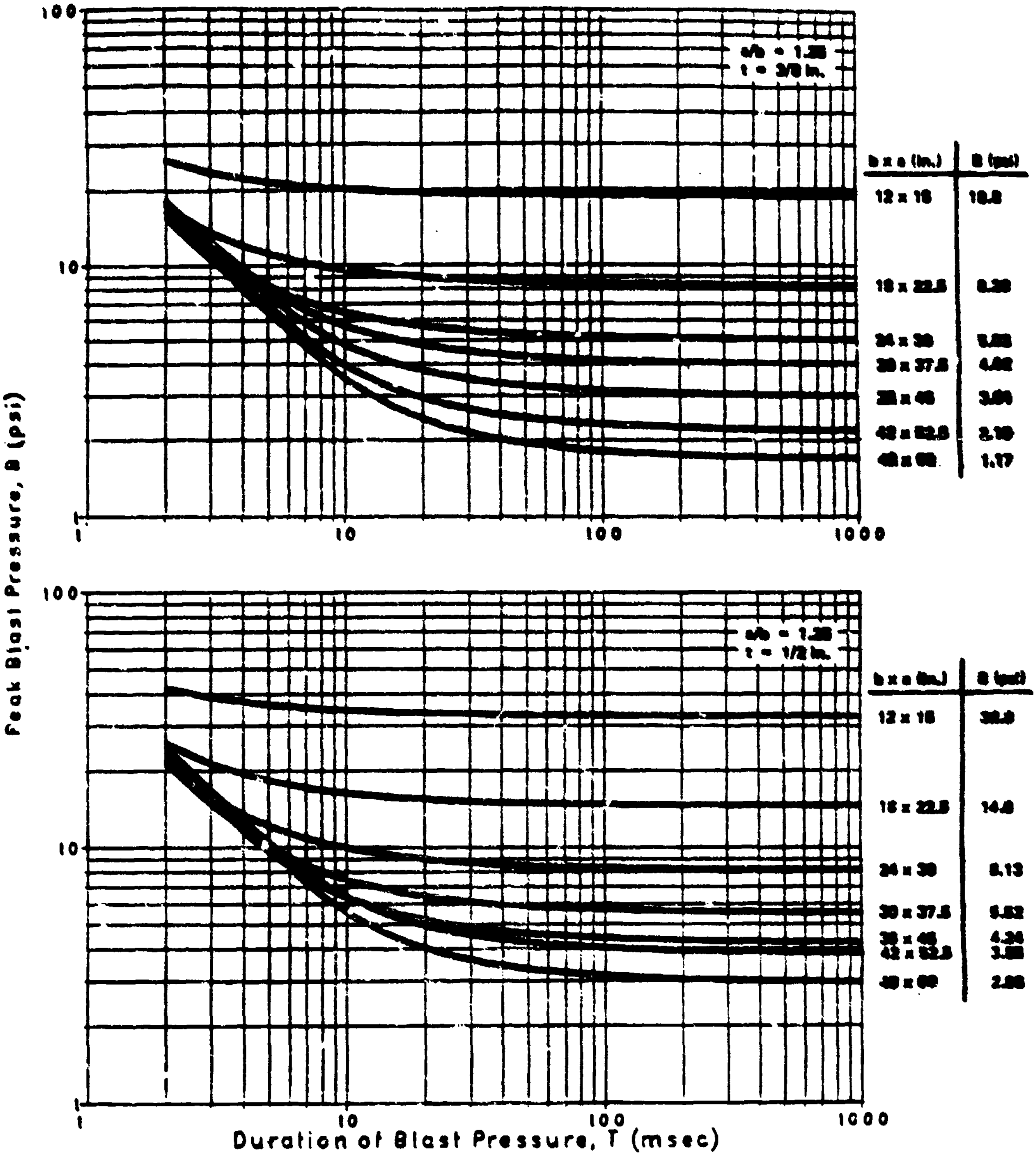


Figure 6. Peak blast pressure capacity for tempered glass panes: a/b = 1.25, t = 3/8 and 1/2 in.

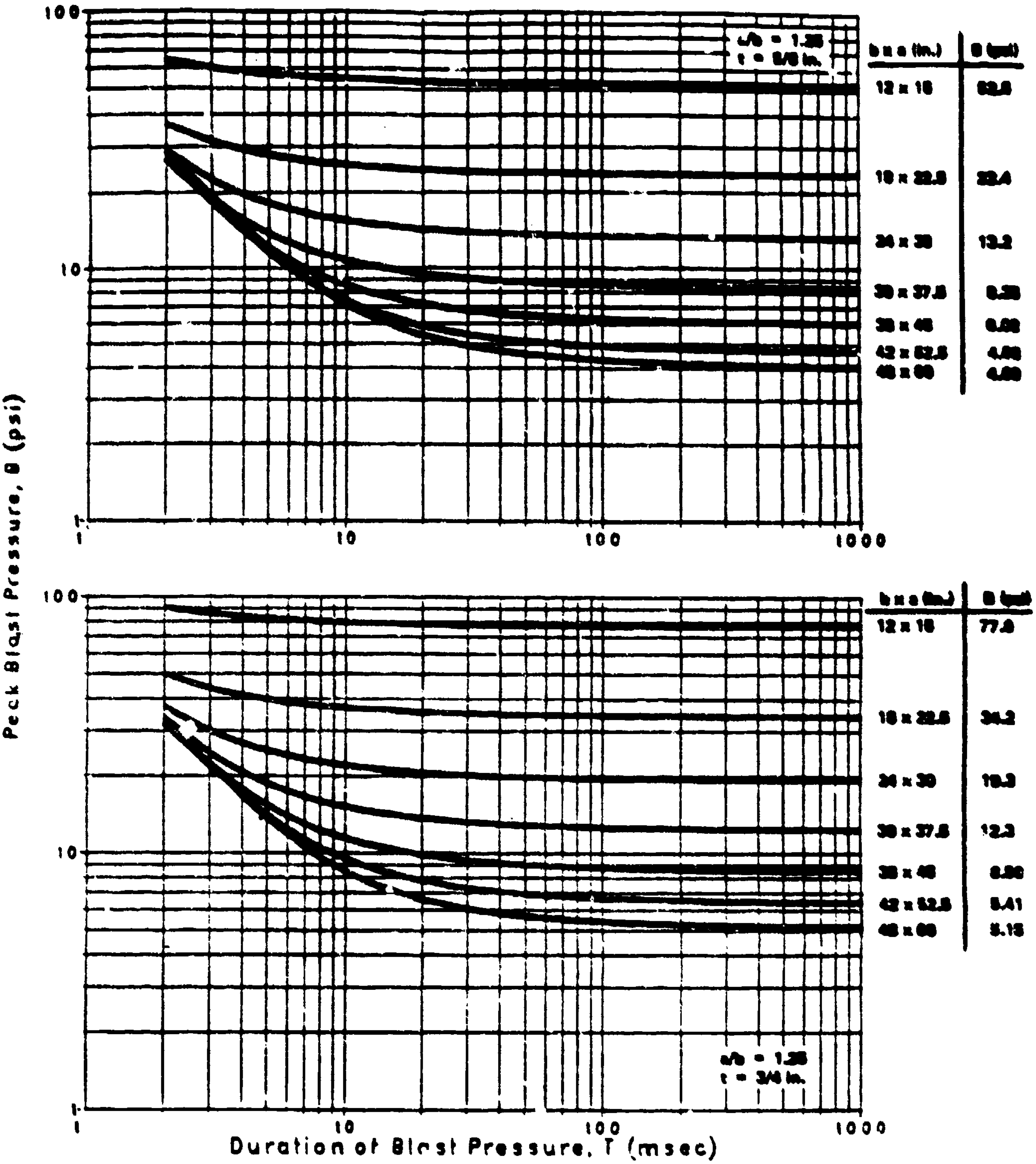


Figure 7. Peak blast pressure capacity for tempered glass panes: a/b = 1.25, t = 5/8 and 3/4 in.

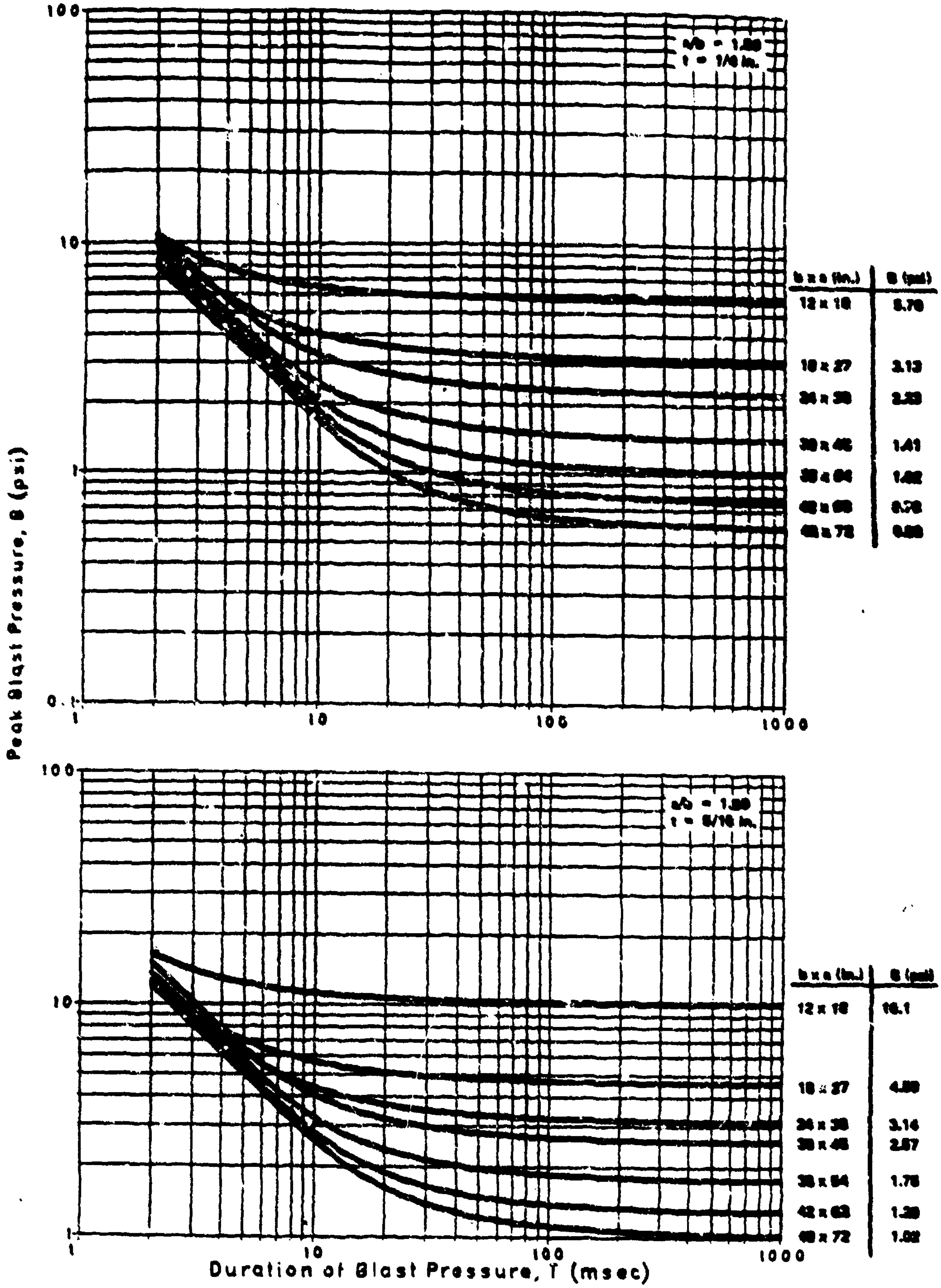


Figure 8. Peak blast pressure capacity for tempered glass panes: a/b = 1.50, t = 1/4 and 5/16 in.

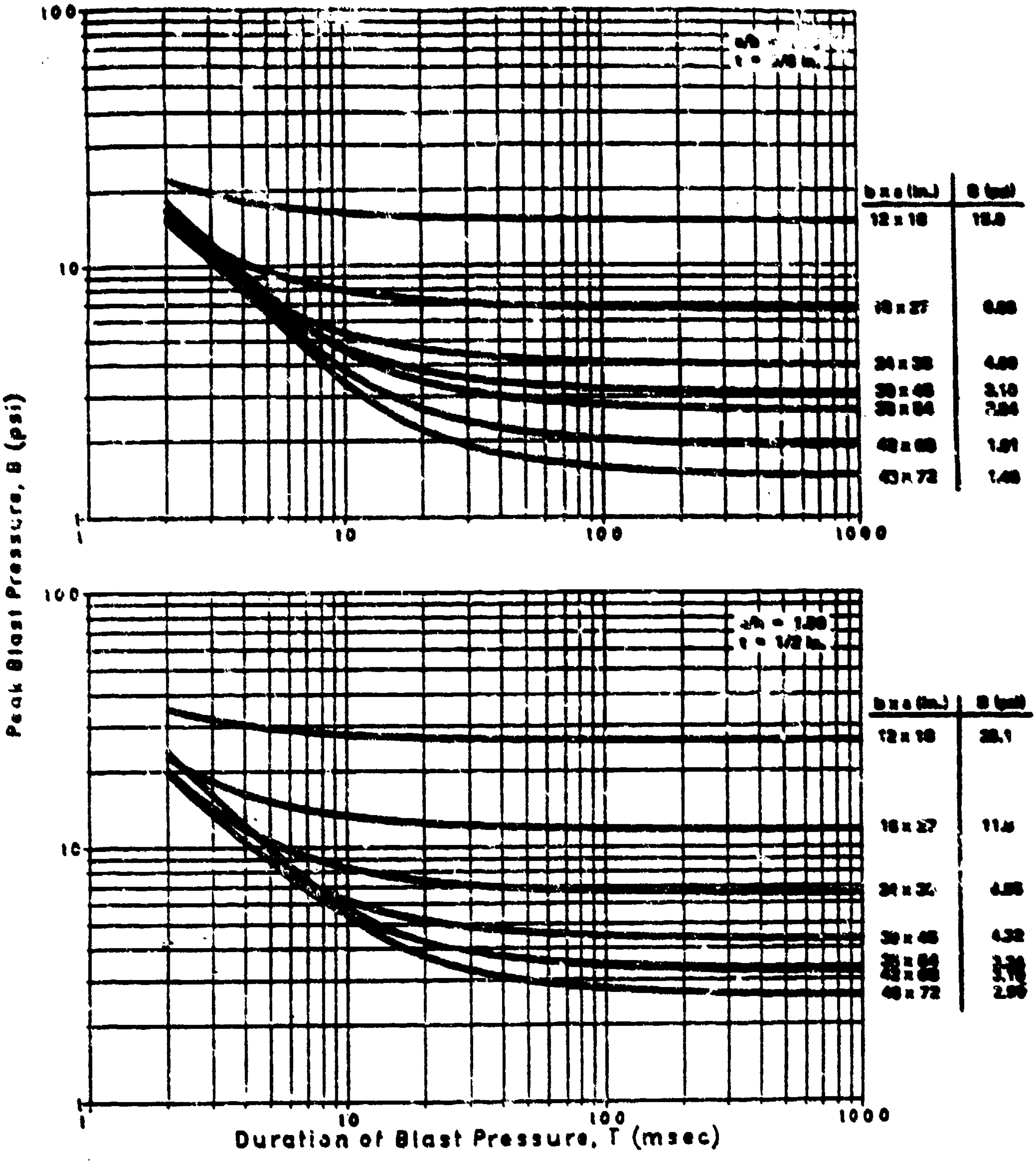


Figure 9. Peak blast pressure capacity for tempered glass panes: a/b = 1.50, t = 3/8 and 1/2 in.

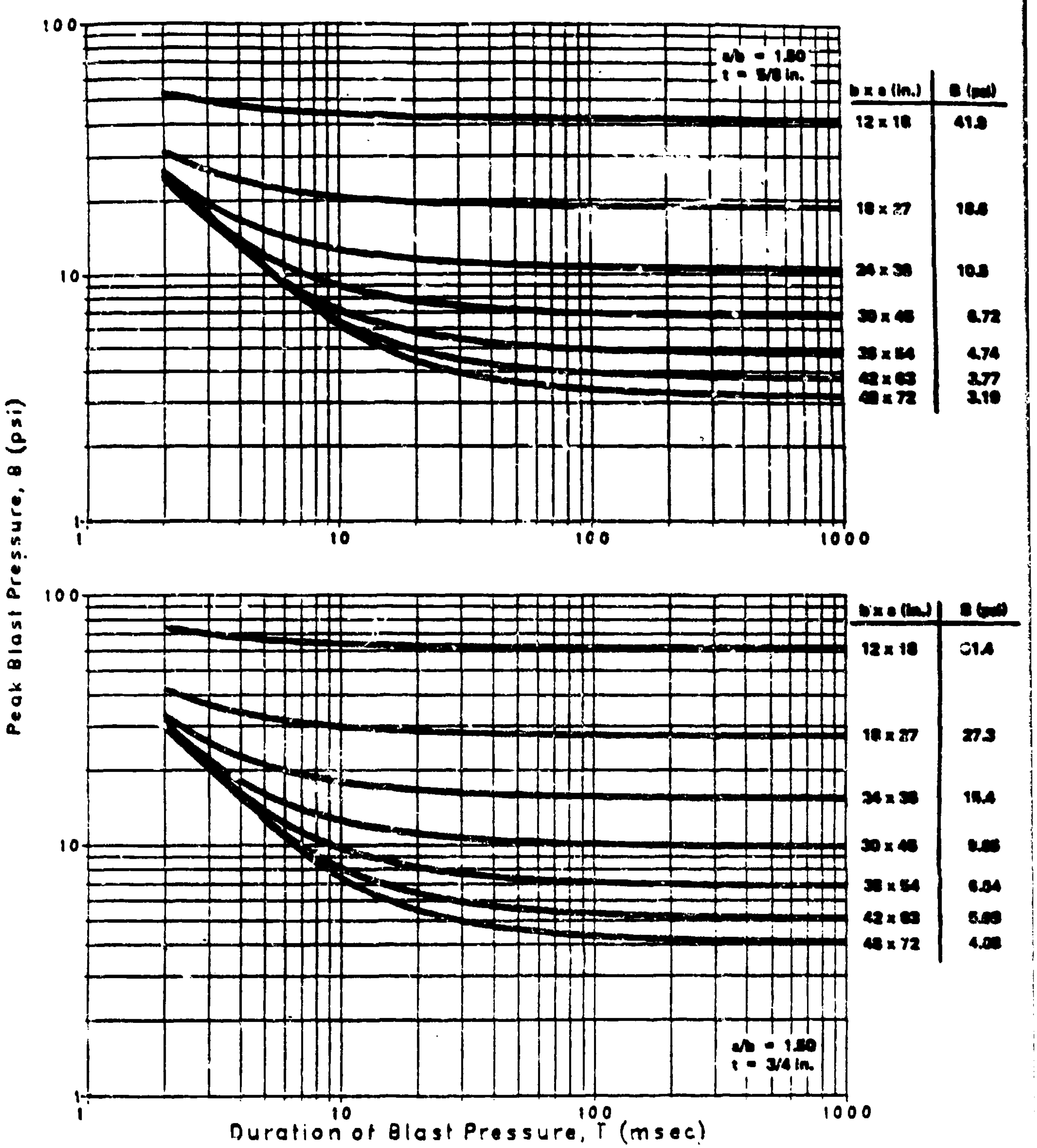


Figure 10. Peak blast pressure capacity for tempered glass panes: a/b = 1.50, t = 5/8 and 3/4 in.

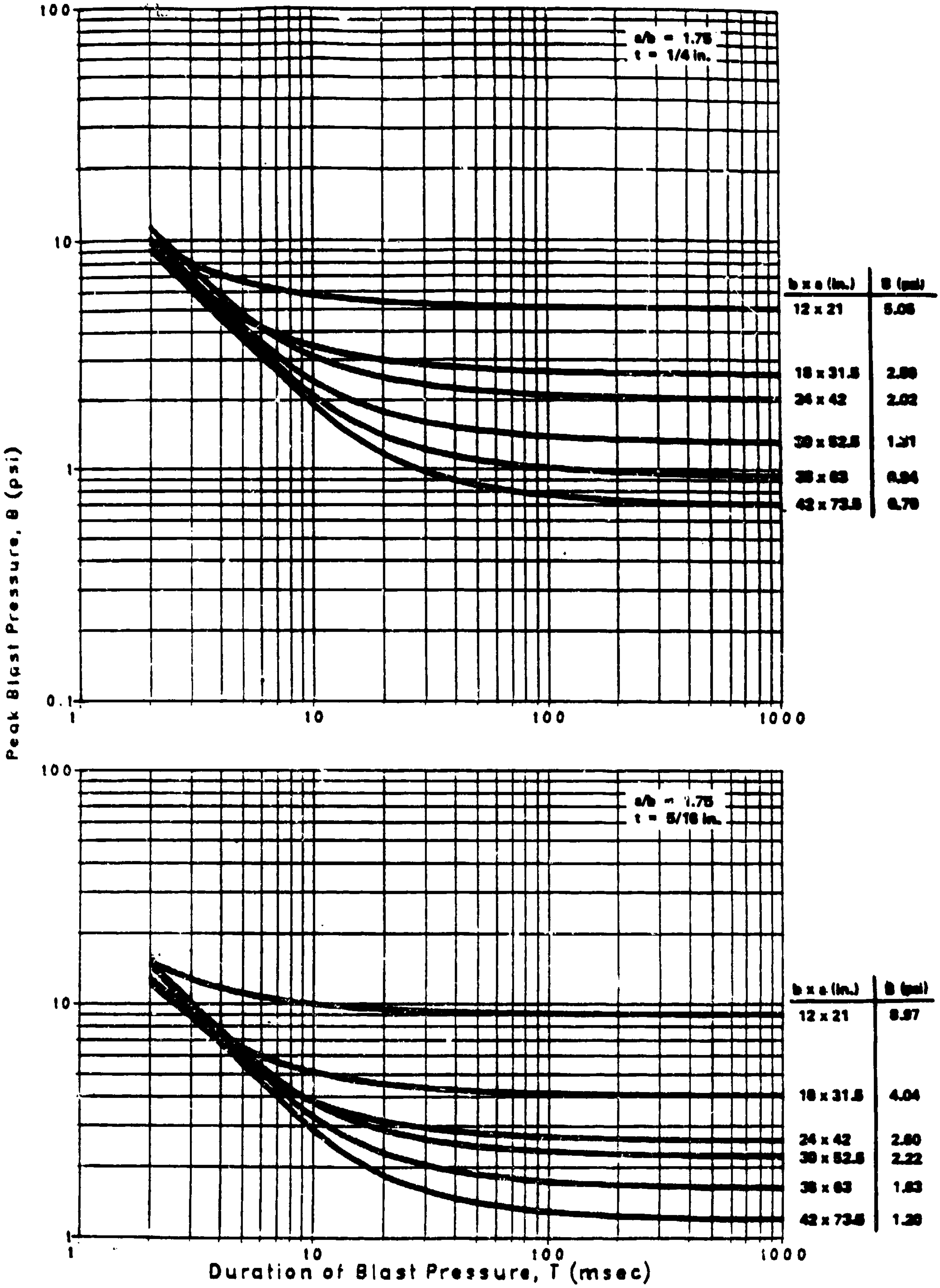


Figure 11. Peak blast pressure capacity for tempered glass panes: a/b = 1.75, t = 1/4 and 5/16 in.

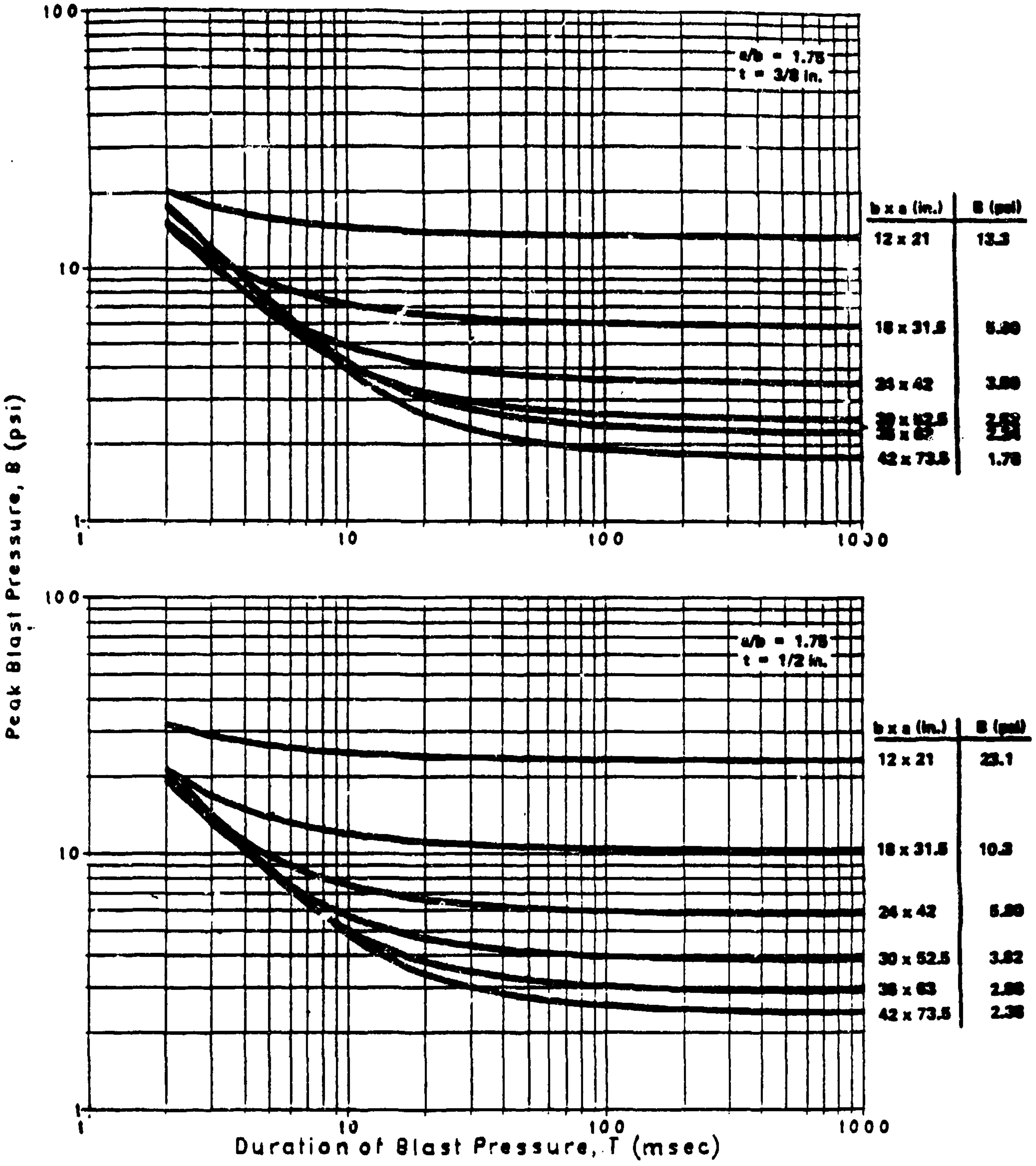


Figure 12. Peak blast pressure capacity for tempered glass panes: a/b = 1.75, t = 3/8 and 1/2 in.

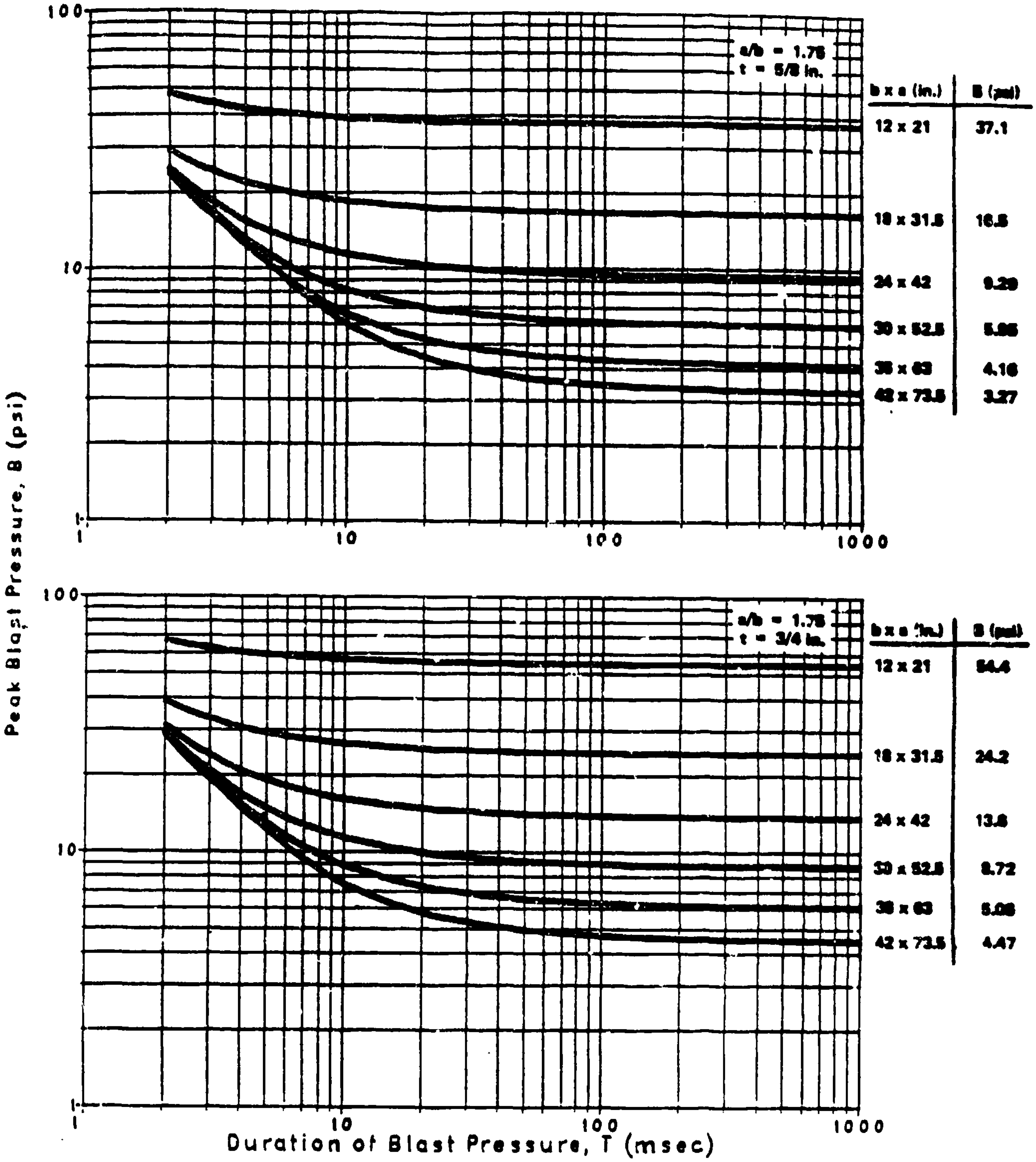


Figure 13. Peak blast pressure capacity for tempered glass panes: a/b = 1.75, t = 5/8 and 3/4 in.

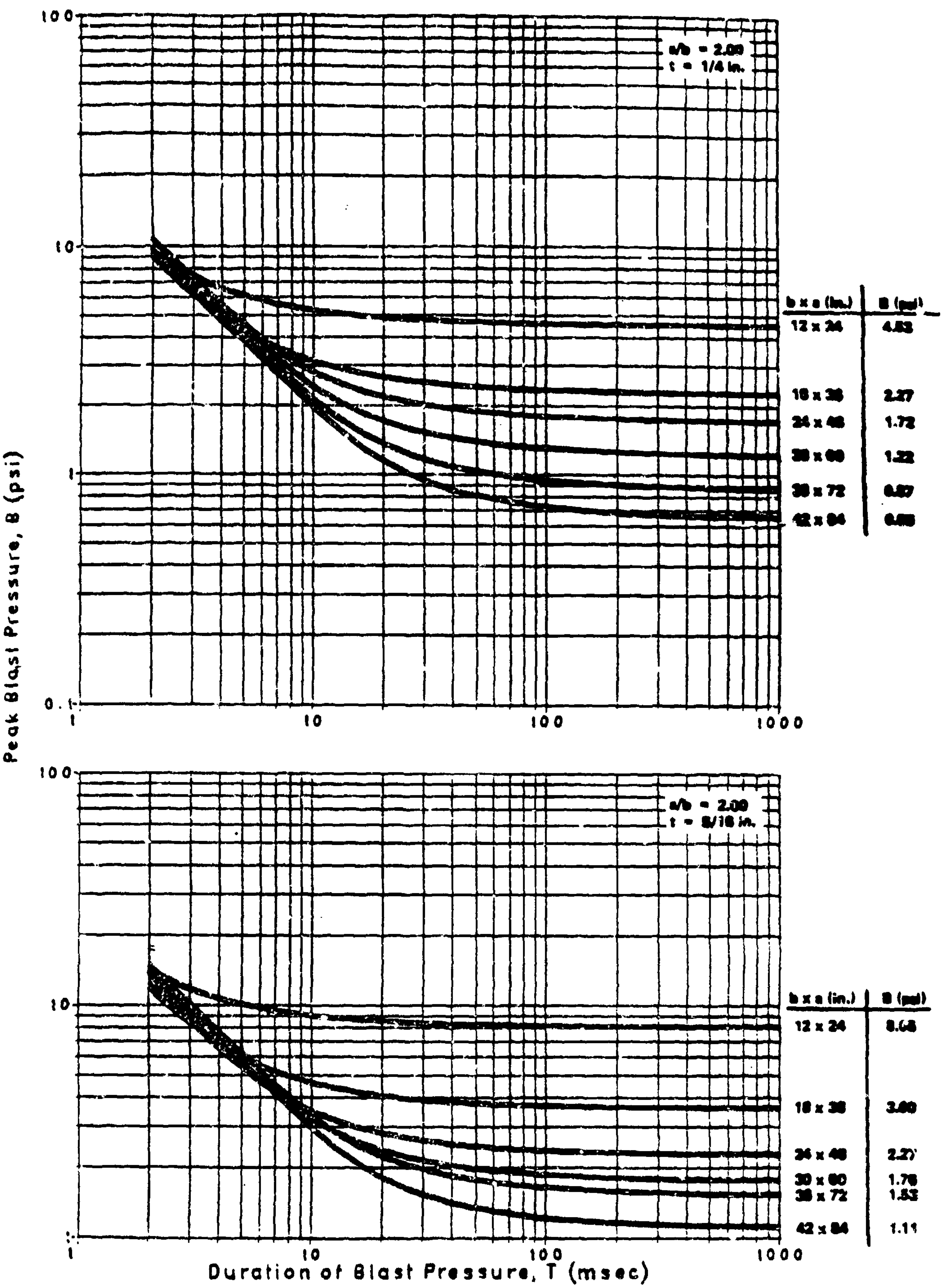


Figure 14. Peak blast pressure capacity for tempered glass panes: a/b = 2.00, t = 1/4 and 5/16 in.

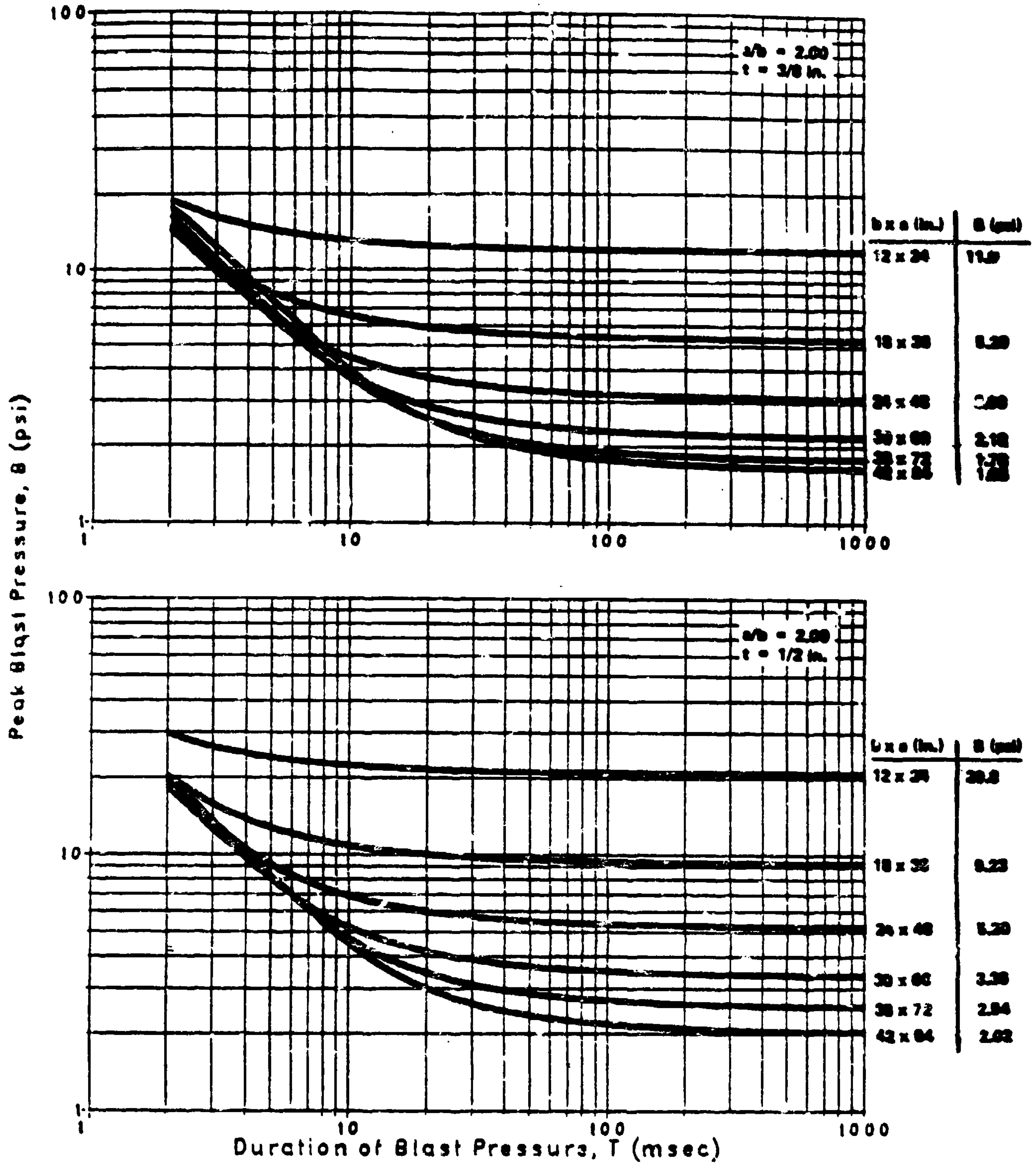


Figure 15. Peak blast pressure capacity for tempered glass panes: a/b = 2.00, t = 3/8 and 1/2 in.

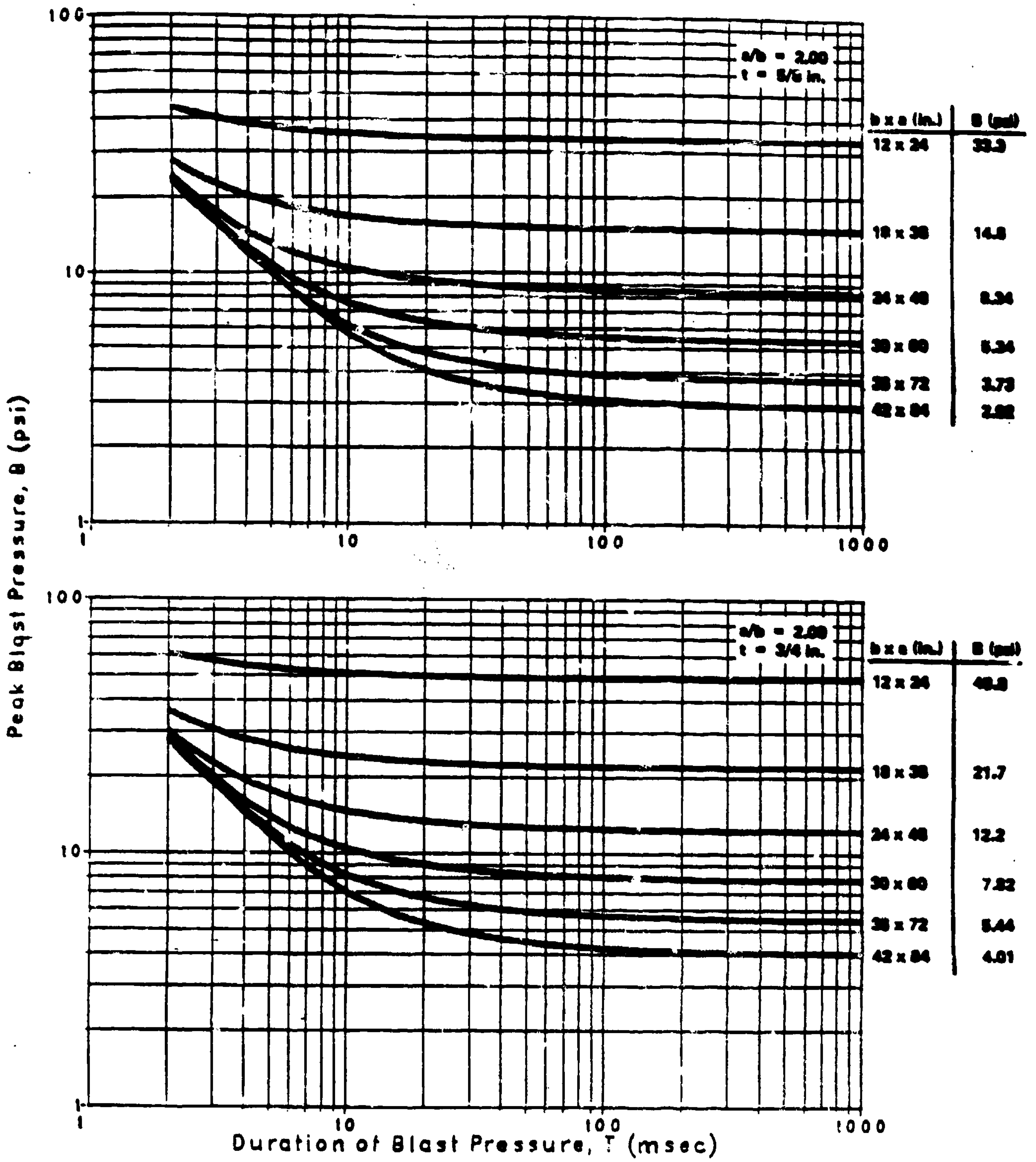


Figure 16. Peak blast pressure capacity for tempered glass panes: a/b = 2.00, t = 5/8 and 3/4 in.

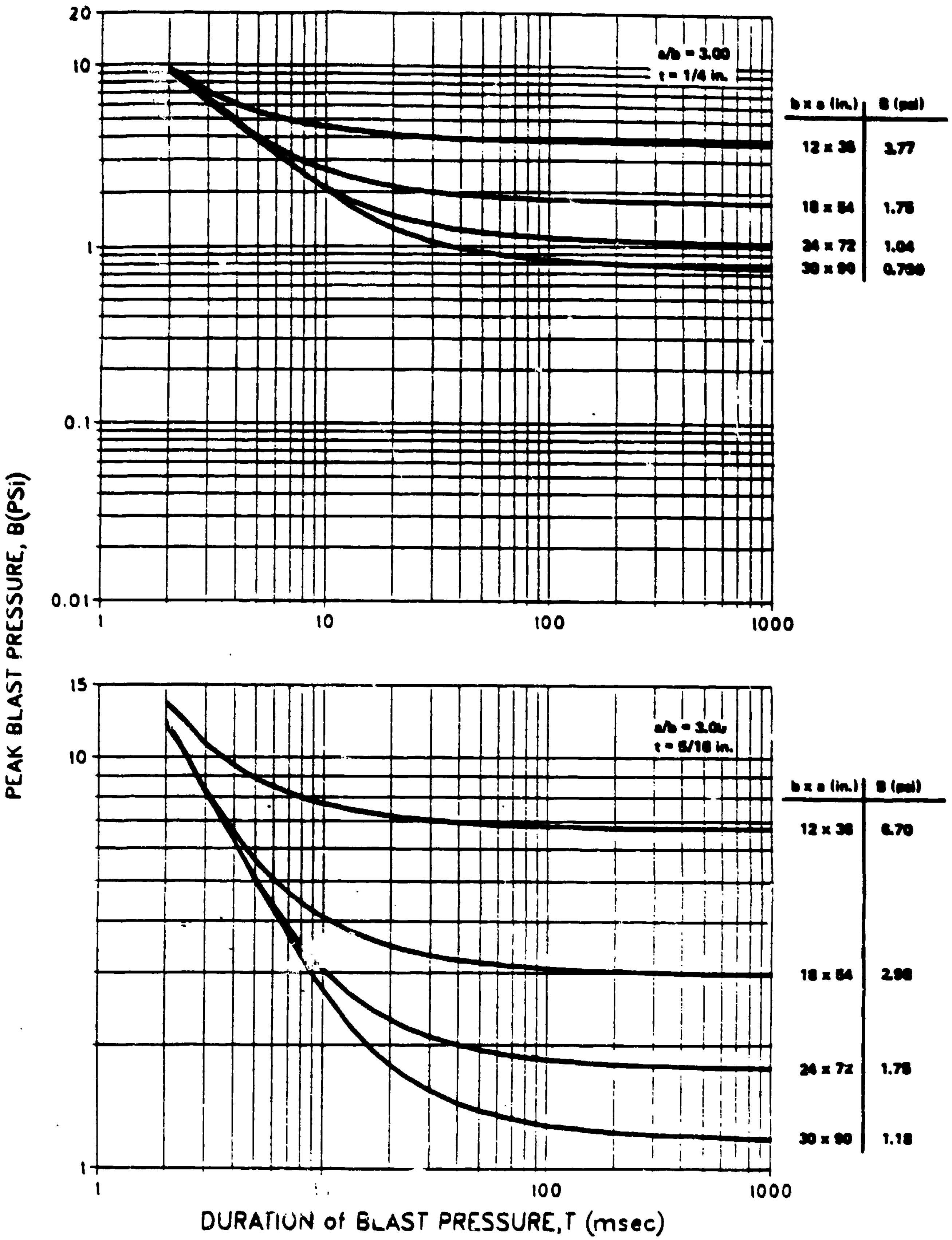


Figure 17. Peak blast pressure capacity for tempered glass panes: a/b = 3.00, t = 1/4 and 5/16 in.

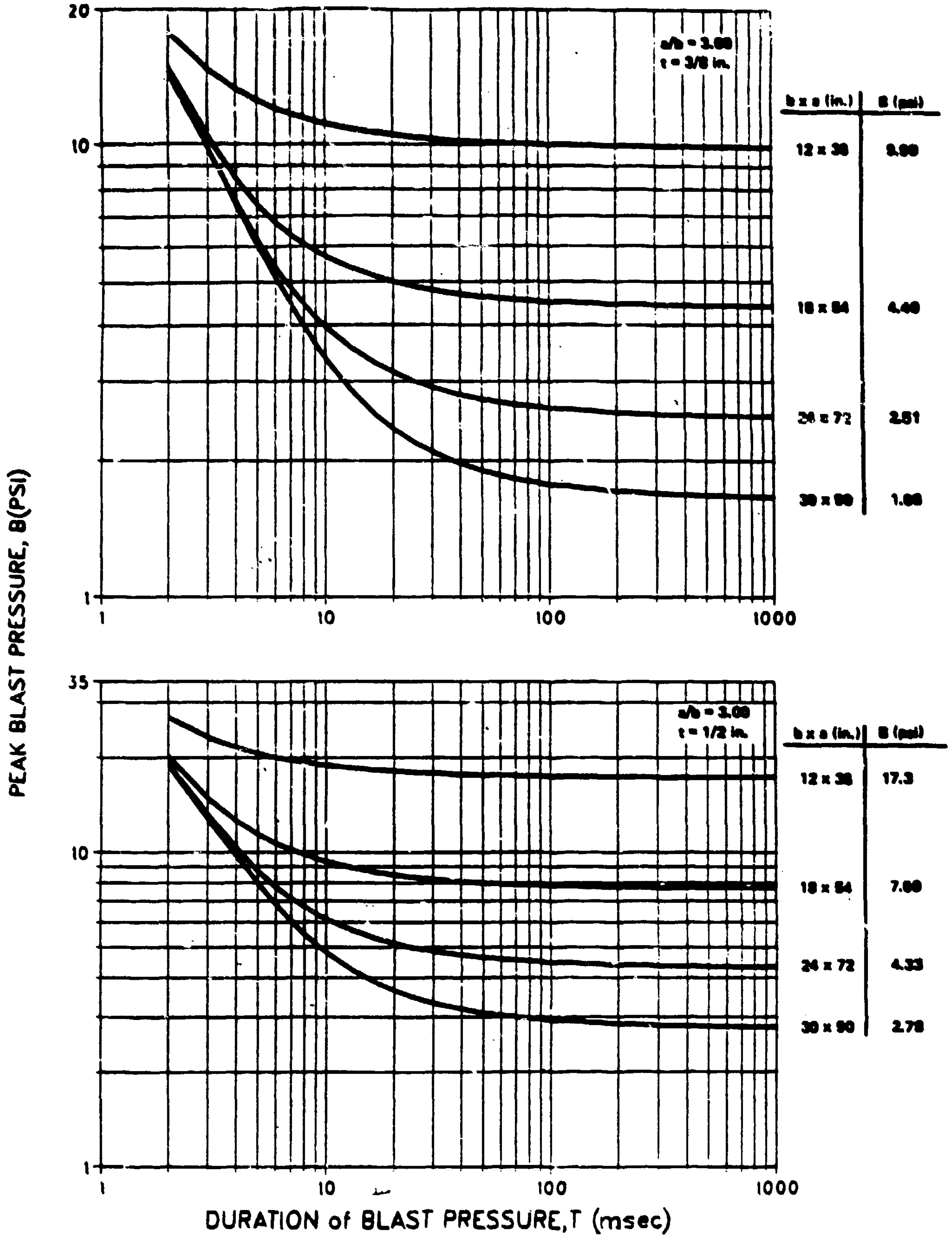


Figure 18. Peak blast pressure capacity for tempered glass panes: a/b = 3.00, t = 3/8 and 1/2 in.

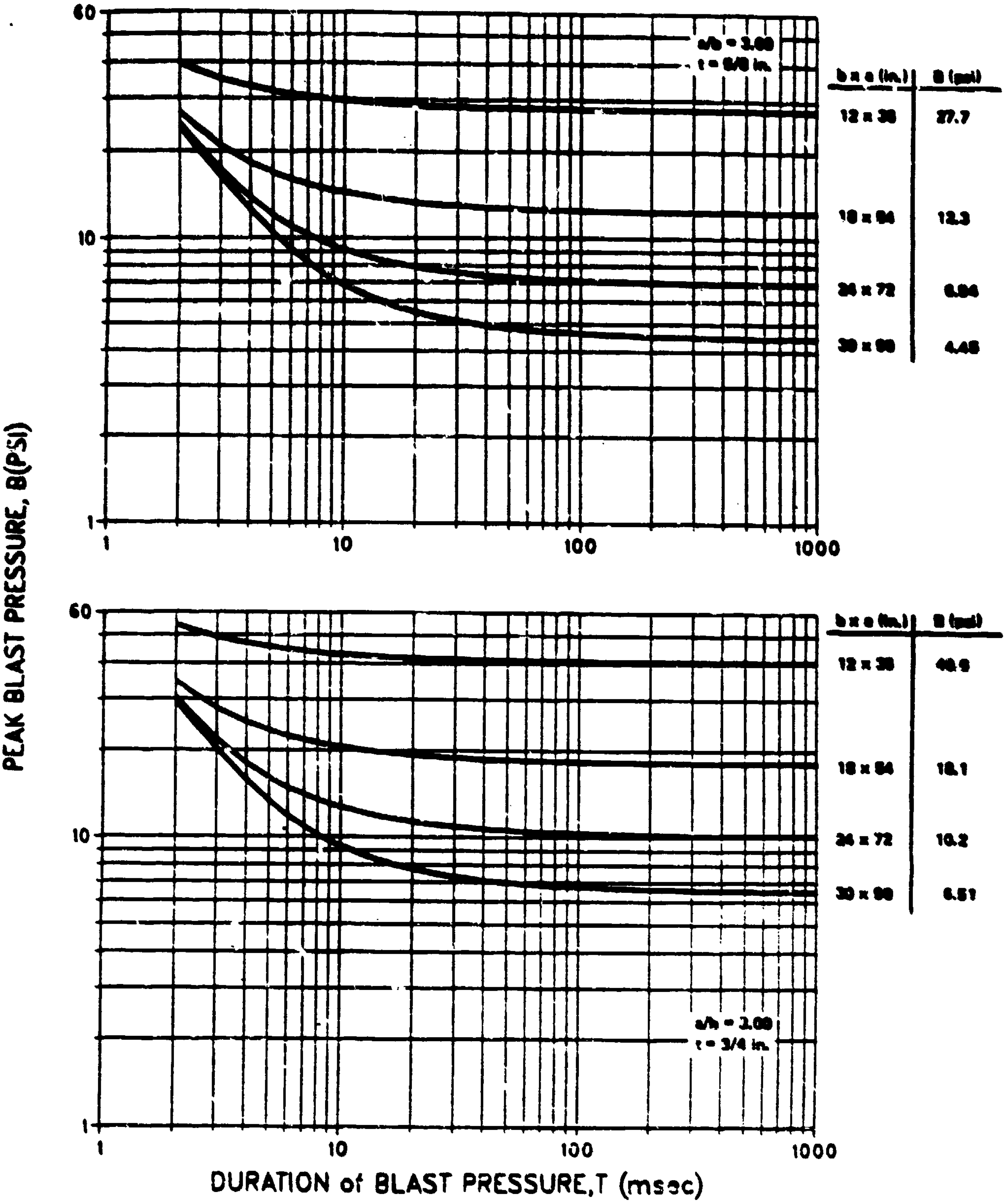


Figure 19. Peak blast pressure capacity for tempered glass panes: a/b = 3.00, t = 5/8 and 3/4 in.

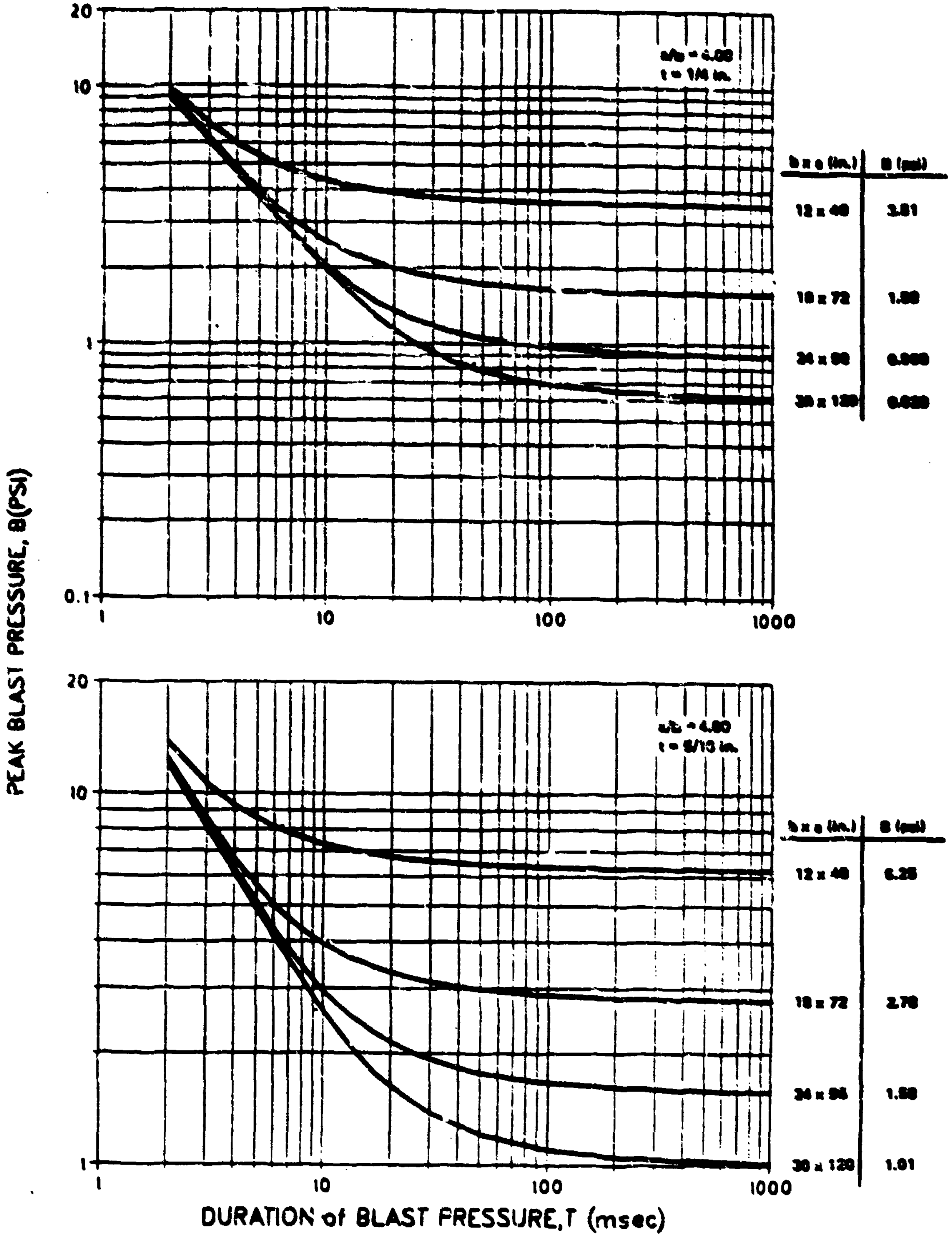


Figure 20. Peak blast pressure capacity for tempered glass panes: a/b = 4.00, t = 1/4 and 5/16 in.

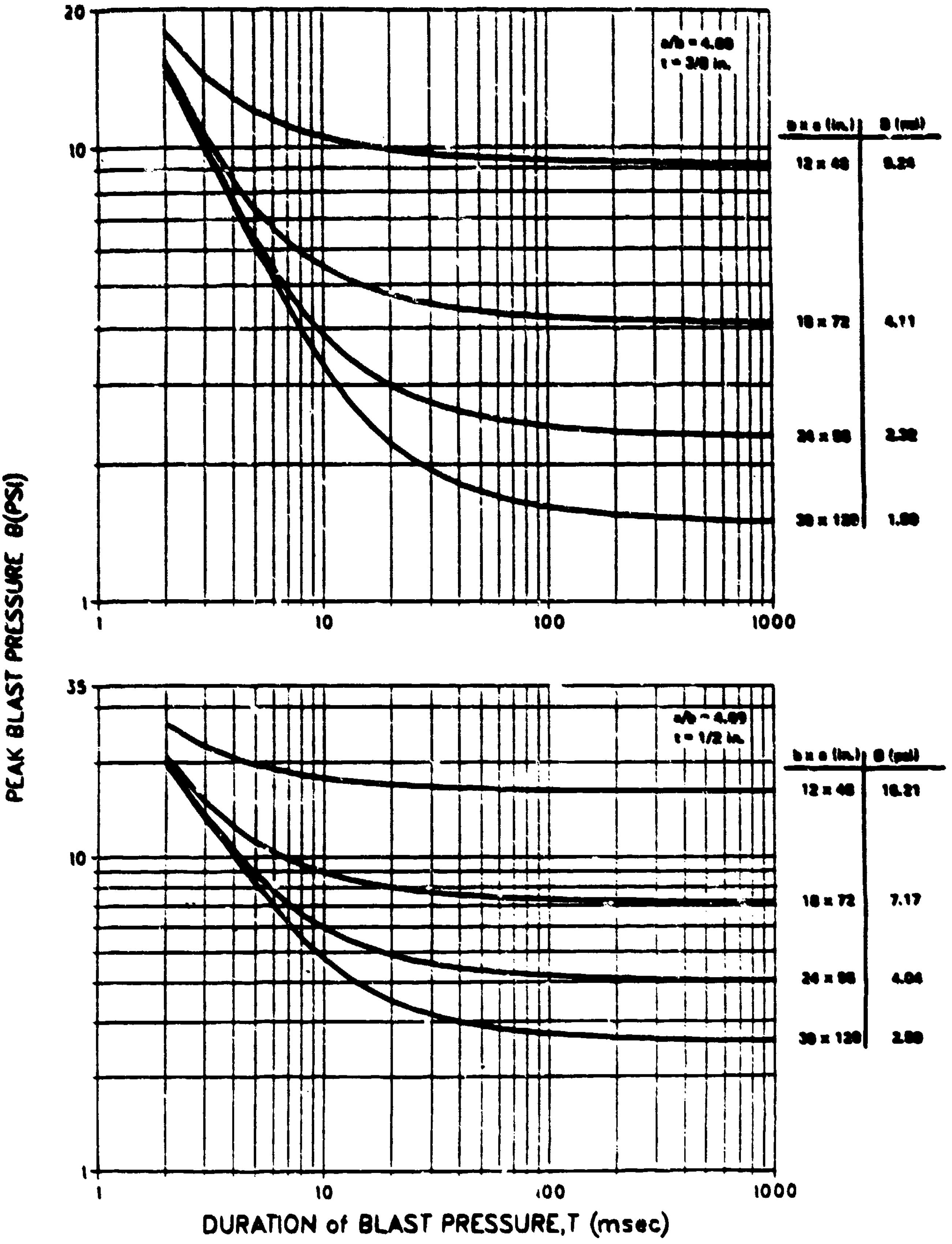


Figure 21. Peak blast pressure capacity for tempered glass panes: a/b = 4.00, t = 3/8 and 1/2 in.

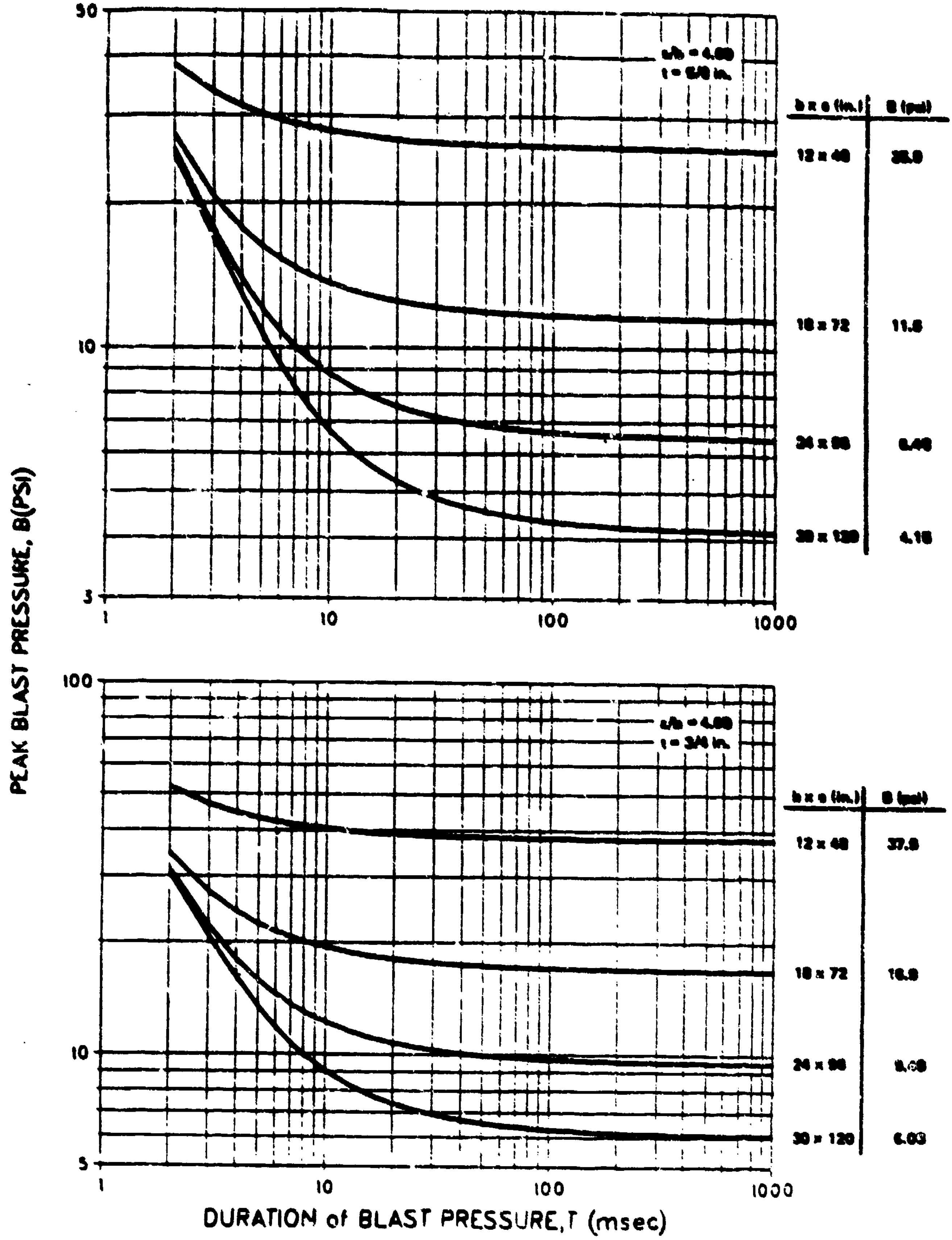


Figure 22. Peak blast pressure capacity for tempered glass panes: a/b = 4.00, t = 5/8 and 3/4 in.

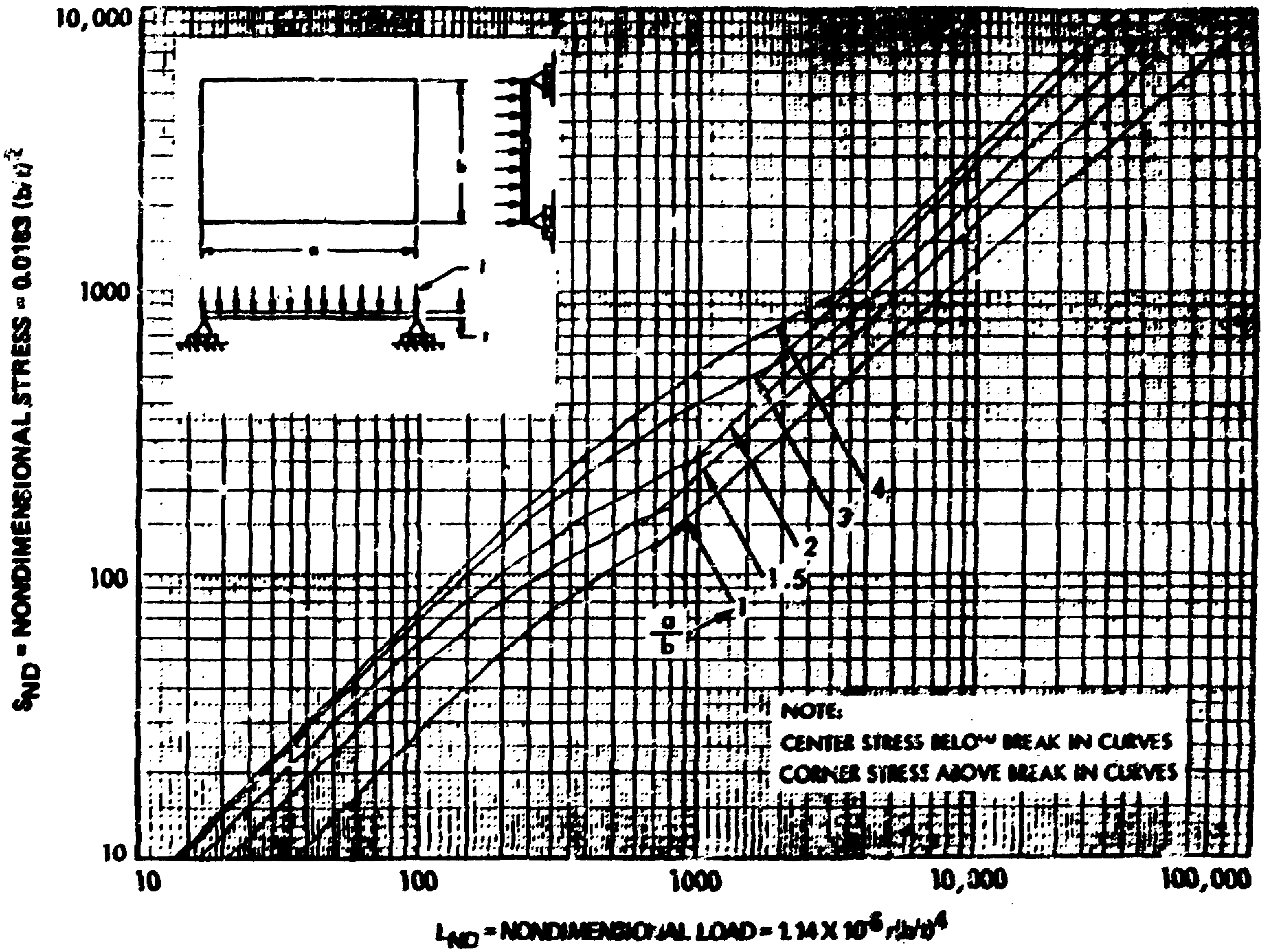


Figure 23. Nondimensional static load-stress relationships for simply supported tempered glass (after Moore).

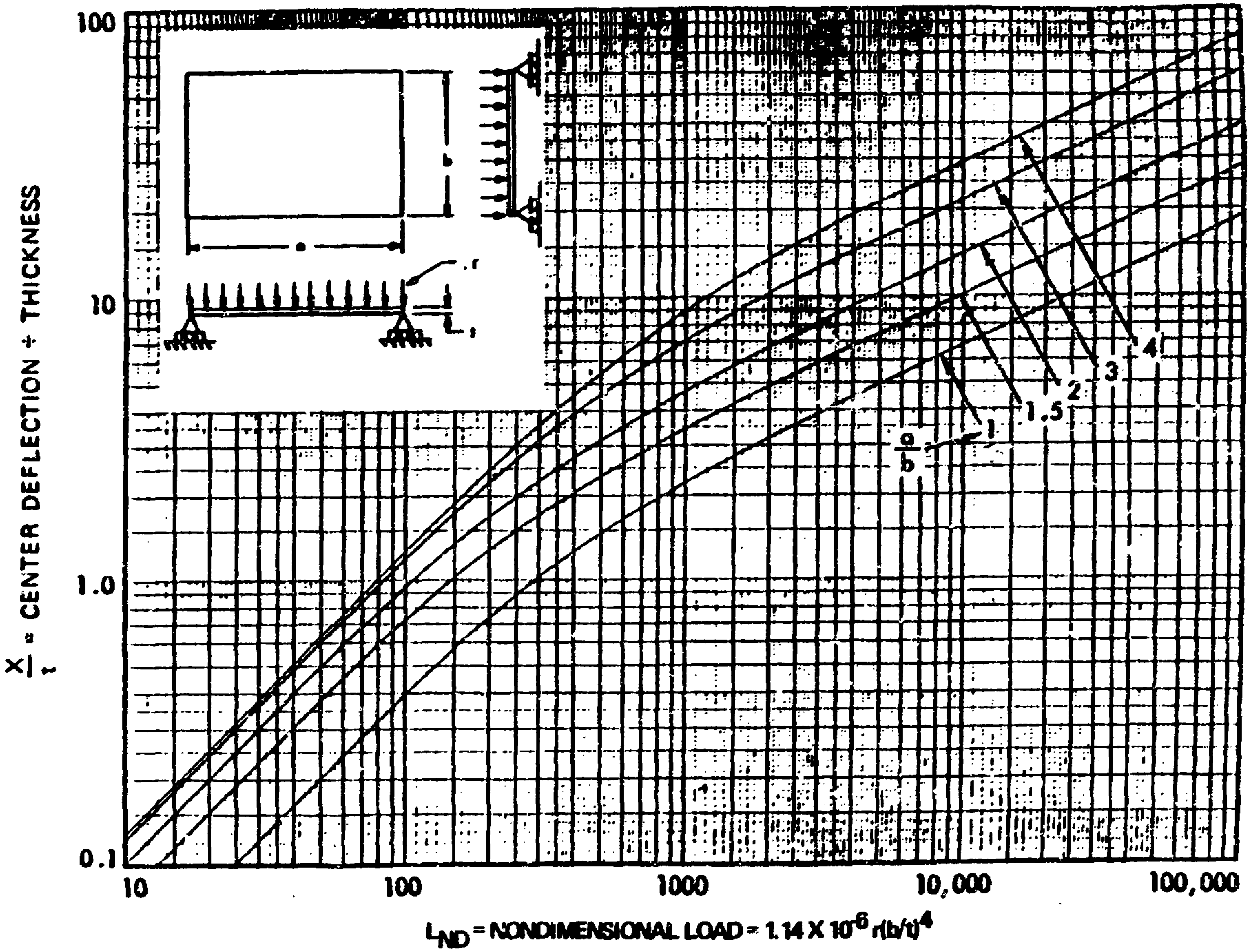
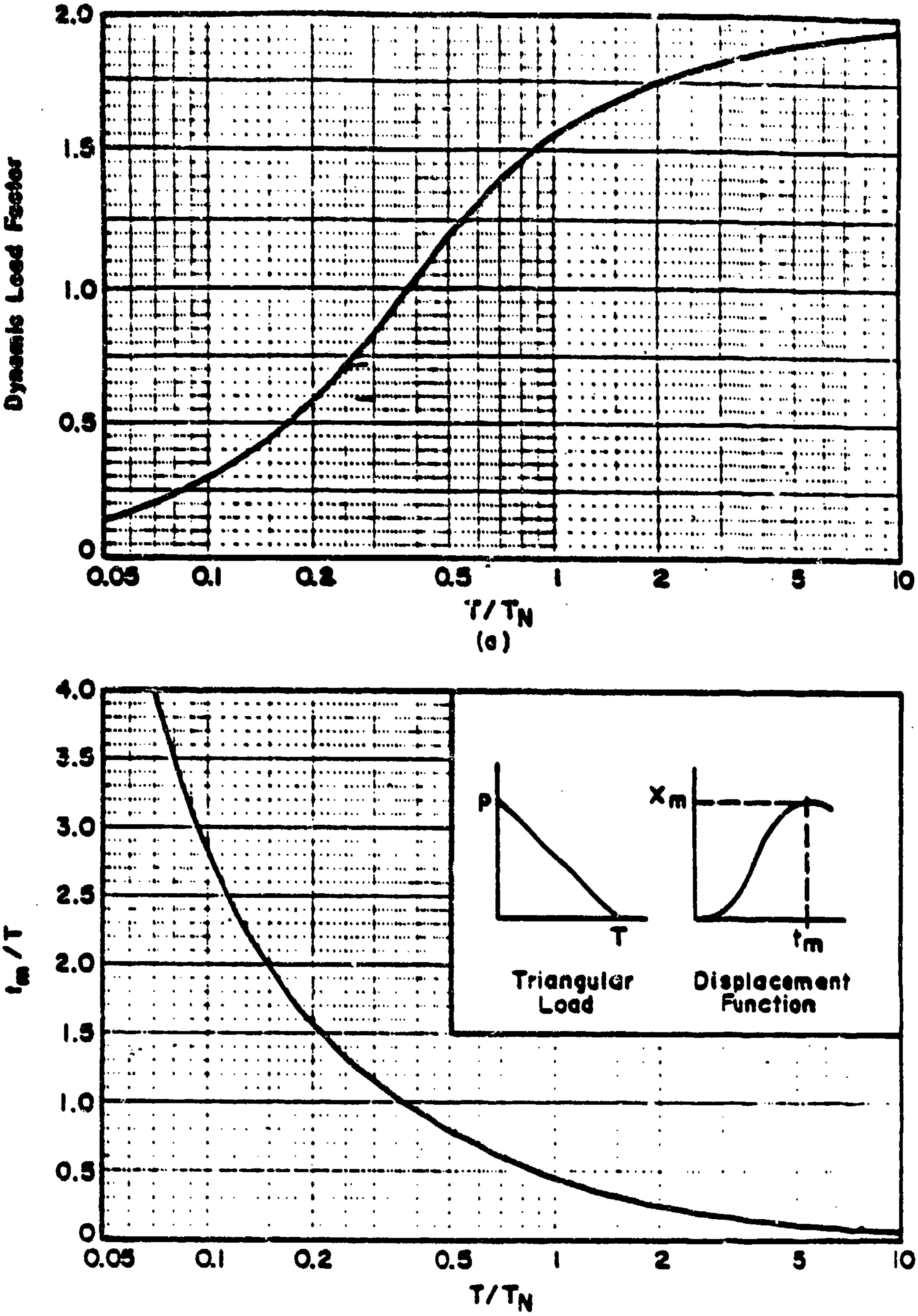


Figure 24. Nondimensional static load-crater deflection relationships for simply supported tempered glass (after Moore).



(a)

(b)

Figure 25. Maximum response of elastic one-degree-of-freedom system for triangular load (Figure 3 - 49 NAVFAC P-397 draft).

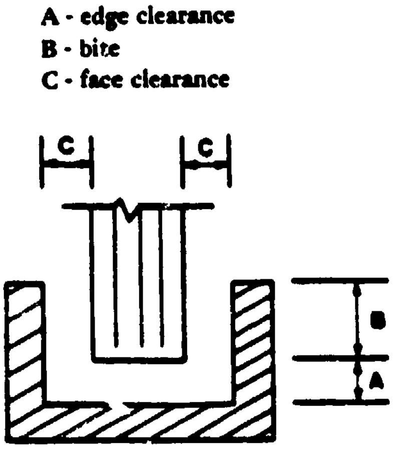


Figure 26. Edge, face, and bite requirements.

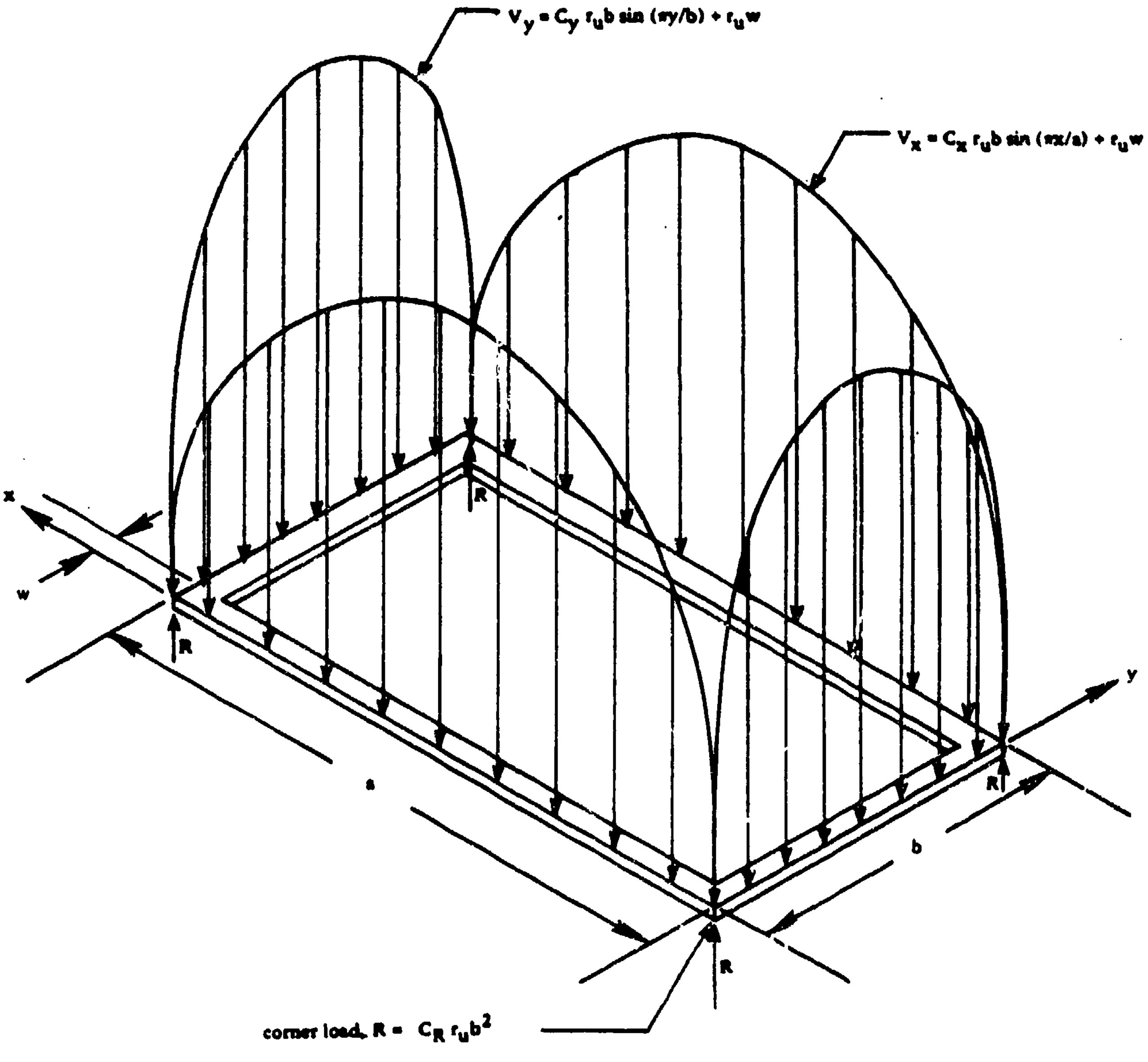

$V_y = C_y r_u b \sin(\pi y/b) + r_u w$
$V_x = C_x r_u b \sin(\pi x/a) + r_u w$
x
w
R
R
R
R
a
b
y
corner load, $R = C_R r_u b^2$

Figure 27. Distribution of lateral load transmitted by glass pane to the window frame.

AD-P005 330

MISSILE TEST CELL DESIGN LOAD
AND SAFE SITING CRITERIA

by

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1.0 INTRODUCTION

1.1 Background

The reliability of today's highly sophisticated weapons systems is dependent on simulation tests. These power-on, all-up tests are required prior to delivery to the fleet and periodically during the life of the missile. The tests must be conducted in hardened missile test cells (MTCs) to prevent communication of an accidental explosion to ordnance outside the cell and to limit leakage pressures in adjacent occupied areas to less than 2.3 psi.

1.2 Problem

Operational requirements make it highly desirable to locate the MTCs directly adjacent to the Assembly Building work bay. In most cases, the Assembly Building is an existing unhardened facility with lightweight metal roofing and walls. To locate the MTC nearby the Assembly Building, the new MTC must be designed to limit the effects of an accidental explosion to less than 2.3 psi on the unhardered building. At the desired short separation distances, and with the present technology, the MTC would be required to almost completely contain the explosion and the resulting long duration gas pressure loads. The excessive cost of a complete containment test cell has made it necessary to develop new concepts for reducing the effects of a contained explosion.

1.3 Potential Solution

Recent tests conducted by the Terminal Effects Research and Analysis Group (TERA) of the New Mexico Institute of Mining and Technology, Socorro, NM, for the Naval Civil Engineering Laboratory (NCEL) and the Naval Surface Weapons Center (NSWC) have indicated that vented areas with frangible surfaces (i.e., a surface that is designed to fail in an explosion and vent the internal gas pressures) reduce the shock loads outside a containment cell. The reduction has been so dramatic that it should be possible to design a frangible panel with sufficient area and mass to adequately vent gas pressures while greatly reducing external shock pressures. The frangible panel must remain in place long enough to reflect shock waves back into the containment cell, but it must also vent the gas pressures quickly enough to keep the gas impulse inside the MTC to a manageable level.

1.4 Purpose

In December 1985, NCEL conducted tests at TERA to determine the blast environment inside and outside a scale model missile test cell. The tests are part of a program to develop Naval Facilities Engineering Command (NAVFAC) standards for missile test cell designs that meet operational requirements of the Naval Sea Systems Command (NAVSEA) and the Naval Air Systems Command (NAVAIR). Test data are presented and used to develop design load and siting requirements for NAVFAC MTCs.

2.0 TEST PROGRAM

The test structure was a 1:2.6 scale model, reinforced concrete, arch-shaped "horseshoe" structure. Dimensions are shown in Figure 1. By volume, the test structure is a 1:2.54 scale model of a rectangular NAVFAC Type I MTC. The important constant parameters were the vent area, $A = 32\ ft^2$, and the volume, $V = 920\ ft^3$. The scaled vent area was $A/V^{2/3} = 0.338$. Scaled vent areas greater than this would result in greater pressures and impulses outside the MTC, while a smaller scaled vent area would reduce the blast environment outside the MTC. The values of fixed parameters in the test structure are as follows:

Parameter	Test Structure
Internal Volume, V (ft^3)	920
Vent Area, A (ft^2)	32
Scaled Vent Area, $A/V^{2/3}$	0.338
Floor Width, L_S (ft)	9.72
Floor Length, L_L (ft)	15.42
L_S/L_L	0.63
Initial Vent Area, A_o (ft^2)	
No Vent Cover (A_o = A)	32
With Vent Cover	0.442
Scaled Initial Vent Area, $A_o/V^{2/3}$	
No Vent Cover (A_o = A)	0.338
With Vent Cover	0.0047

Variable parameters in the test program included the TNT equivalent explosive weight, W (pounds), the vent cover weight, w (psf), and the recess of the vent cover, x (feet). The scaled parameters using these variables are the scaled distance ($Z = R/W^{1/3}$), the charge density (W/V), the scaled cover weight ($\bar{w} = w/W^{1/3}$), and the scaled cover recess ($\bar{x} = x/W^{1/3}$). The range of parameters in the test program were:

Parameter	Range of Parameter Values for Model Test Structure
Explosive Weight, W (lb TNT)	4.52 to 40.7
Scaled Weight of Vent Cover, $w/W^{1/3}$ (psf/lb$^{1/3}$)	0 to 40.6
Scaled Recess of Vent Cover, $x/W^{1/3}$ (ft/lb$^{1/3}$)	0 to 0.88

All vent covers included a 9-inch-diameter (A_o = 0.442 ft^2; $A_o/V^{2/3}$ = 0.0047) cutout to account for uncovered openings in the MTC cover.

Table 1 summarizes the test program and the variables in each test. The arch cross section should not be a factor in applying the test results to rectangular structures provided the aspect ratio of the floor is close to that of the model.

3.0 TEST RESULTS

3.1 External Loads

The incident blast environment outside the MTC was measured at the ground locations shown in Figure 2. Gages are designated by a letter code for direction ("F" = Front; "S" = Side; "D" = Diagonal; "B" = Back) and a number code for range (the number corresponds to one-tenth the range in feet: R/10). For example, the gage designation F8 indicates a gage to the front of the MTC at a range of 80 feet.

Digitized data results are summarized in Tables 2 through 8. These tables show peak pressures and scaled impulses versus gage location and test variables (e.g., $\bar{w}$ and $\bar{x}$). Each table is for a constant W and W/V. All tests used a vent area of 32 ft^2 but varied the mass and recess of the vent cover.

Two pressure-time plots at gage 2 for Test 10 (without a cover) and Test 13 (with a cover) are shown in Figure 3. The two plots show the variations in pressure histories that are possible at the same location and for similar peak pressures and impulses. Use of an equivalent triangular load-time history is generally conservative and is sufficient for all the data used in this report.

The data in Tables 2 through 8 are plotted in Figures 4 through 19. Each figure includes the hemispherical surface burst curve for comparison. Figures 4 through 7 show the directional effects of the MTC on the blast environment with no vent cover ($\bar{w}$ = 0). Figures 8 through 10 show the effect of charge density, W/V, on peak pressures and scaled impulses with $\bar{w}$ = 0. Figures 11 through 19 show the effect of vent cover weight, w, and recess, x, on the blast environment.

The test results show that the tested MTC geometry and vent cover had the following general effects on the external blast environment compared to that from an unconfined hemispherical surface burst (the basis for NAVSEA OP-5 quantity distance relationships):

1. Front Direction - significant increase in pressure and impulse (over that of an unconfined hemispherical surface burst) without vent cover; increase in scaled impulse but no change in peak pressure with vent cover.
2. Side Direction - significant decrease in pressure and impulse without vent cover; variable effect with vent cover although usually small for $W/V > 0.015$.
3. Back Direction - very significant decrease with or without cover; the decrease with cover was less (except for heavy covers and large charge densities).

3.2 Internal Gas Pressure Loads

The internal gas pressure loads were measured by gages G1, G3, and G4 located inside the MTC (Figure 1). Digitized data results are summarized in Tables 2 through 8. The data results include peak gas pressure and scaled impulse. The scaled impulses, shown in these tables for comparison only, were scaled by the TNT equivalent weight for shock ($W = 1.13 \times$ weight of C4 explosive). Scaling by the gas pressure equivalent weight would require a variable factor as determined by the procedure in NAVFAC P-397. See Section 7.2 for determination of design gas pressure loads. The test results show that, as expected, the peak gas pressure is a function of W/V, and the scaled gas impulse, given a constant vent opening, depends on the mass of the cover, w, and its recess, x. The results show that the procedure in NAVFAC P-397 for determining gas pressure and impulse applies to MTC design. See Section 7.0 for the internal design gas pressure and shock loads.

4.0 SITING CRITERIA

For the remotely controlled testing in a MTC, NAVSEA OP-5 requires a scaled separation distance of 24 $ft/lb^{1/3}$. This is the scaled distance at which a hemispherical surface burst produces a peak incident blast overpressure, P_{so}, of 2.3 psi. Because of the directional effects of the MTC on the external blast environment, the scaled distance to the back of the MTC where P_{so} is 2.3 psi is significantly reduced from that for a surface burst. "B" direction overpressure data are plotted in Figure 20 for tests without vent covers ($\bar{w} = 0$). An average slope of the data was determined from best fit power curves using data nearest 2.3 psi and for $0.015 \leq W/V \leq 0.045$ lb/ft$^{1/3}$. The data for $W/V = 0.005$ lb/ft^3 were not used because the overpressures were too low (< 0.5 psi). Data used are identified in Figure 20 by the solid symbols. The average slope was then used to derive the upper bound straight line relationships shown in Figure 20. As can be seen from the surface burst curves in Figures 4 through 19, straight line relationships (on log-log plots) are accurate for interpolation of free-field overpressure data over full cycle (factor of 10) ranges of P_{so}. The Z values corresponding to 2.3 psi from these upper bound curves are considered reasonable and safe for developing the siting criteria for points to the back of the MTC.

The upper bound Z values corresponding to $P_{so} = 2.3$ psi and no vent cover are plotted against W/V in Figure 21. In order to safely account for the effects of pressure reflections from vent covers, worst case Z values from all cover tests at W/V values of 0.015 and 0.045 lb/ft^3 were obtained from the test data. The following table shows Z values with and without vent covers and shows their ratio, F_r. F_r was calculated from worst case test data for $W/V = 0.015$ and 0.045 lb/ft^3. F_r for $W/V = 0.025$ lb/ft^3 (for which there were no data with vent covers) was obtained from linear interpolation between the other F_r values, and a resulting Z_r, with cover, was calculated.

W/V	Z_o	Z_r	F_r
0.015	6.45	8.0[a]	1.24
0.25	8.8	11.4[b]	1.30[c]
0.045	10.0	14.2[a]	1.42

Z_o = Z for 2.3 psi; $\bar{w} = 0$, from Figure 20

Z_r = Z for 2.3 psi; worst case for all $\bar{w}$ and $\bar{x}$

$F_r = Z_r/Z_o$

[a] From test data.
[b] Calculated from $Z_r = F_r \times Z_o$.
[c] From linear interpolation between other F_r values.

The Z_r values to limit P_{so} to 2.3 psi to the back of the MTC are plotted in Figure 21. The relationship applies to the following ranges of parameters:

$0.015 \leq W/V \leq 0.045$ lb/ft^3

$0 \leq \bar{w} \leq 40$ psf/lb$^{1/3}$

$0 \leq \bar{x} \leq 0.88$ ft/lb$^{1/3}$

$A/V^{2/3} < 0.35$

$L_S/L_L = 0.63$ (±10%)

where: L_S = short floor dimension

L_L = long floor dimension

and vent in short wall

For the NAVFAC Type I MTC, W/V = 0.02 lb/ft^3, and from Figure 21, the safe Z for P_{so} = 2.3 psi to the back of the MTC is 9.7 ft/lb$^{1/3}$. With a rated capacity of 300 pounds, the safe distance to the rear is $9.7 \times 300^{1/3}$ = 65 feet measured from the outside of the vented wall.

5.0 DESIGN EXTERNAL BLAST LOADS

Measured blast loads were used to derive design blast loads in each direction outside the MTC. Results are shown in Figures 22 through 25. The design blast loads are based on data for $0.015 \leq W/V \leq 0.045$ lb/ft^3. Design curves are summarized in Figure 26 for the design peak incident overpressure, P_{so}, and in Figure 27 for the design scaled incident impulse, $i_s/W^{1/3}$. The design curves apply to a MTC for the same range of parameters listed above for siting the Missile Processing Building. Note that siting criteria separation distances (Section 4.0) are expressed as a function of charge density (W/V), whereas design load relationships are conservatively based on worst case results for all parameters, including W/V.

5.1 "F" Direction

The blast loads to the front of the MTC ("F" Line in Figure 2) are enhanced by the focusing of shock waves escaping through the front wall vent. The effect is especially apparent without a vent cover. Peak overpressures, however, were essentially equal to those of a hemispherical surface burst for all tested vent covers ($9 \leq \bar{w} \leq 40$ psf/lb$^{1/3}$ and $0 \leq \bar{x} \leq 0.9$ ft/lb$^{1/3}$). Figure 22 shows worst case data and the upper bound peak overpressure design curves recommended for points to the front of a MTC. When a vent cover with $9 \leq \bar{w} \leq 40$ psf/lb$^{1/3}$ is used, the P_{so} relationship for a hemispherical surface burst may be used. Scaled impulse data were also higher with no vent cover. Therefore, in Figure 23, two scaled impulse design curves are shown for two ranges of scaled cover weight ($\bar{w}$).

5.2 "S" Direction

Worst case peak overpressure and scaled impulse to the side of the MTC ("S" Line in Figure 2) are plotted in Figure 24. Peak overpressures, from all tests (with and without vent covers) are adequately described by the hemispherical surface burst relationship. The upper bound envelope for scaled impulse, however, deviates from the surface burst relationship, at $Z < 40$ ft/lb$^{1/3}$, as shown in Figure 24.

5.3 "B" Direction

The blast loads to the back of the MTC are less than those of a hemispherical surface burst. Worst case peak pressure and scaled impulse data are plotted in Figure 25 for tests with and without vent covers. Recommended design load curves are also shown in Figure 28 which, for all but a single point, are upper bounds on the pressure and impulse data.

5.4 Design Load Summary

Figures 26 and 27 summarize the design loads outside a MTC. Figure 26 presents the design peak incident overpressure, P_{so}, in the three major directions from the MTC. The range, R (ft), is measured from the outside center of the vent cover in the front wall. The mid-range curve is identical to the hemispherical surface burst relationship for P_{so} and applies to the side direction for all $\bar{w}$ and to the front direction for $9 \leq \bar{w} \leq 40$ psf/lb$^{1/3}$. As shown by the curves, the blast environment is greatest in the front direction with $0 \leq \bar{w} < 9$ psf/lb$^{1/3}$ and the least in the back direction with or without a vent cover.

The scaled incident impulse design curves are shown in Figure 27. Two curves, for different ranges of $\bar{w}$, are required to show the design relationships to the front of the MTC. The relationships for the side and back directions apply with or without vent covers. The hemispherical surface burst curve is shown for comparison.

The load relationships in Figures 26 and 27 are limited to the ranges of parameters stated in the Figures and in Section 4.0 above.

6.0 INHABITED BUILDING QUANTITY-DISTANCE REQUIREMENTS

Figure 26 is used to define the inhabited building distance (IBD) in each direction from NAVFAC Type I (or similar) MTCs. The IBD is the distance corresponding to P_{so} = 1.2 psi. The safe distance to public traffic routes is 60% of IBD, in accordance with NAVSEA OP-5. From Figure 26 you obtain the following values for K:

K $(ft/lb^{1/3})^a$ for Inhabited Building Distance

Front[b]		Side	Back
$0 \le \bar{w} < 9$	$9 \le \bar{w} < 40$		
62	40	40	24

[a] Public traffic route quantity-distance requirements are 60% of IBD requirements.

[b] Fragments and debris from vent will require at least 1,250 feet within a 60-degree cone to front for inhabited buildings and 750 feet to front for public traffic routes.

7.0 DESIGN INTERNAL LOADS

The MTC must be designed to contain the design explosive weight of the Maximum Credible Event (MCE) from a warhead detonation. The reinforced concrete roof, sidewalls, and backwall must be designed to safely withstand the loads from a warhead detonation. The design loads consist of the initial shock wave loads from the explosive detonation and the long duration gas pressure loads caused by the containment of the products of detonation.

7.1 Shock Loads

Shock loads are determined with the computer program IMPRESS. IMPRESS, developed by Ammann and Whitney Consulting Engineers for ARRADCOM, is the basis for the internal shock loads provided in the revised NAVFAC P-397 Design Manual. The MTC geometry and envelope of

MCE locations are used to determine the critical location of the explosive. The TNT equivalent explosive weight for shock pressure is determined and a 1.2 factor of safety is applied to obtain the explosive weight:

$$W_{DESIGN} = W \times \text{TNT Equivalency} \times 1.2$$

IMPRESS or NAVFAC P-397 may be used to obtain an idealized triangular design shock load with peak pressure B_1 and duration T_1 as shown in Figure 28.

7.2 Gas Pressure Loads

Containment of the products of detonation creates a relatively low pressure and long duration gas pressure loading. NCEL has developed a computer program using theoretical and empirical methods to determine the gas pressure loading. The computer program, REDIPT, is described in a paper presented at the 21st DDESB Seminar: "Effect of Frangible Panels on Internal Gas Pressures," by J.E. Tancreto and E.S. Helseth, August 1984. The revised NAVFAC P-397 Design Manual uses data plots from REDIPT as the design internal gas pressure loads for containment structures.

The TNT equivalent explosive weight for determining gas pressures is calculated from the ratios of heats of combustion and heats of detonation as shown in NAVFAC P-397. A 1.2 factor of safety is applied when determining structural design loads. The design equivalent weight for gas pressure loads is calculated from the product of the actual explosive weight, the TNT equivalency, and the factor of safety, as in the equation given above for shock pressure design explosive weight. The design charts in NAVFAC P-397 are then used to calculate the idealized gas pressure loading with peak pressure B_2 and duration T_2 as shown in Figure 28.

7.3 Combined Total Internal Design Load

Due to the methods used in experimentally measuring gas pressure, the shock and gas pressure triangular load-histories should be merged, as shown in Figure 28, rather than added. A bilinear load function results with a maximum pressure = B_1 at T = 0 and a duration of T_2. The intersection of the shock and gas pressure triangular load functions is at the B_i, T_i point:

$$T_i = \frac{(B_1 - B_2)\ T_1\ T_2}{(B_1\ T_2 - B_2\ T_1)}$$

$$B_i = B_1 \left(1 - \frac{T_i}{T_1} \right)$$

or

$$B_i = B_1 \left[1 - \frac{(B_1 - B_2)\ T_2}{B_1\ T_2 - B_2\ T_1} \right]$$

Table 1. MTC Test Parameters

NCEL Test No.	W (lb)	W/V (lb/ft³)	w (psf)	$\bar{w}$[a] (psf/lb$^{1/3}$)	x (ft)	$\bar{x}$[b] (ft/lb$^{1/3}$)
101	4.52	0.005	0[c]	0	0	0
2	4.52	0.005	31.25	18.90	0.0625	0.03
3	4.52	0.005	31.25	18.90	0.79	0.47
4	4.52	0.005	31.25	18.90	1.45	0.87
5	4.52	0.005	67.2	40.64	1.45	0.87
6	13.56	0.015	0	0	0	0
106	13.56	0.015	0	0	0	0
18	13.56	0.015	31.25	13.10	0.0625	0.02
19	13.56	0.015	31.25	13.10	1.66	0.69
7	13.56	0.015	47.7	20.00	0.094	0.03
8	13.56	0.015	47.7	20.00	1.05	0.44
9	13.56	0.015	91.4	38.33	2.1	0.88
109	22.6	0.025	0	0	0	0
10	40.7	0.045	0	0	0	0
11	40.7	0.045	31.25	9.08	0.0625	0.01
12	40.7	0.045	31.25	9.08	1.66	0.48
13	40.7	0.045	67.2	19.53	0.135	0.03
14	40.7	0.045	67.2	19.53	1.66	0.48
17	40.7	0.045	134	38.96	1.66	0.48

[a] $\bar{w} = w/W^{1/3}$

[b] $\bar{x} = x/W^{1/3}$

[c] Zero indicates no cover over vent opening.

Table 2. Peak Pressure ($W = 4.52$ lb; $W/V = 0.005$ lb/ft^3)

Gage	Scaled Distance, Z (ft/lb$^{1/3}$)	Peak Pressures (psi) for NCEL Test Nos.—				
		101[a]	2[b]	3[c]	4[d]	5[e]
		External Incident Pressures, P_{so}				
F1	6.06	43.4	11.5	9.35	21.9	18.4
F2	12.1	18.6	4.39	3.96	9.58	7.41
F3	24.2	3.92	1.17	1.1	0.85	0.63
F8	48.5	0.93	0.58	0.57	0.47	0.44
F12	72.7	0.47	0.42	0.34	0.29	0.31
S1	6.06	8.86	4.63	5.13	21.5	20.8
S2	12.1	4.14	2.55	2.48	14.3	11.1
S4	24.2	1.01	1.18	0.69	1.0	1.08
S8	48.5	0.49	0.31	0.3	0.37	0.54
D2	12.1	1.18	1.35	0.92	1.37	1.62
D4	24.2	0.44	0.73	0.41	0.53	0.57
D8	48.5	0.22	0.3	0.23	0.24	0.27
B2	12.1	0.52	0.67	0.58	0.67	0.55
B3	18.2	0.42	0.49	0.48	0.53	0.4
B4	24.2	0.25	0.3	0.4	0.33	0.28
B8	48.5	0.21	0.21	0.35	0.23	0.2
		Internal Gas Pressures, P_g				
G1	f	31	41	46	49	48
G3	f	24	--	--	45	44
G4	f	26	38	41	48	47

[a] No cover.

[b] $\bar{w} = 18.9$; $\bar{x} = 0.04$.

[c] $\bar{w} = 18.9$; $\bar{x} = 0.48$.

[d] $\bar{w} = 18.9$; $\bar{x} = 0.88$.

[e] $\bar{w} = 40.6$; $\bar{x} = 0.88$.

[f] Internal gas pressure gage on wall. Distance not a factor.

Table 3. Scaled Impulse (W = 4.52 lb; W/V = 0.005 lb/ft^3)

Gage	Scaled Distance, Z (ft/$lb^{1/3}$)	Scaled Impulse (psi-ms/$lb^{1/3}$) for NCEL Test Nos.--				
		101[a]	2[b]	3[c]	4[d]	5[e]
External Incident Impulse, $i_s/W^{1/3}$						
F1	6.06	51.65	17.53	16.32	59.27	41.73
F2	12.1	26.61	7.31	9.07	31.45	30.84
F4	24.2	9.07	3.02	3.20	3.32	3.14
F8	48.5	2.96	1.63	1.75	1.66	1.69
F12	72.7	2.41	1.02	1.14	1.08	1.02
S1	6.06	7.01	7.37	9.67	36.89	30.84
S2	12.1	5.56	4.53	5.92	26.00	18.99
S4	24.2	3.08	2.54	2.47	2.29	1.69
S8	48.5	1.51	1.08	1.14	1.08	0.90
D2	12.1	2.72	3.02	2.84	2.90	2.05
D4	24.2	1.75	1.75	1.63	1.57	1.33
D8	48.5	0.96	0.96	0.90	0.90	0.78
B2	12.1	1.99	2.35	2.05	2.17	1.63
B3	18.2	1.93	2.05	2.41	2.35	2.11
B4	24.2	1.27	1.93	1.75	1.63	1.39
B8	48.5	0.84	1.08	1.02	1.02	0.78
Internal Gas Impulse, $i_g/W^{1/3}$						
G1	f	115	549	682	780	986
G3	f	191	--	--	702	898
G4	f	215	505	641	721	961

[a] No cover.

[b] $\bar{w} = 18.9$; $\bar{x} = 0.04$.

[c] $\bar{w} = 18.9$; $\bar{x} = 0.48$.

[d] $\bar{w} = 18.9$; $\bar{x} = 0.88$.

[e] $\bar{w} = 40.6$; $\bar{x} = 0.88$.

[f] Internal gas pressure gage on wall. Distance not a factor.

Table 4. Peak Pressure (W = 13.56 lb; W/V = 0.015 lb/ft^3)

Gage	Scaled Distance, Z (ft/lb$^{1/3}$)	Peak Pressures (psi) for NCEL Test Nos.—						
		6[a]	106[a]	18[b]	19[c]	7[d]	8[e]	9[f]
		External Incident Pressures, P_{so}						
F1	4.19	103.7	83.9	31.9	19.9	27.1	26.4	
F2	8.38	39.5	46.5	13.3	6.43	9.07	7	
F4	16.8	8.47	9.35	3.74	3.28	2.87	3.34	4.39
F8	33.5	2.56	2.63	1.33	1.04	1.11	1.23	0.93
F12	50.3	1.45	1.55	0.75	0.63	0.69	0.65	0.68
S1	4.19	24.5	27.0	17.7	18.2	23.1	13.1	
S2	8.38	8.09	8.86	13.7	9.75	8.57	12.9	
S4	16.8	2.16	1.63	2.3	2.39	2.23	2.27	2.7
S8	33.5	0.79	0.86	1.06	1.26	0.86	1.33	0.94
D2	8.38	2.4	2.48	3.38	2.69	4.16	3.45	3.24
D4	16.8	0.84	1.0	1.54	1.57	1.48	1.7	1.6
D8	33.5	0.4	0.41	0.68	0.65	0.54	0.72	0.64
B2	8.38	1.29	1.66	1.38	1.38	2.17	1.96	1.78
B3	12.6	0.99	0.97	1.05	1.18	1.25	1.33	1.11
B4	16.8	0.78	0.65	0.96	0.97	0.98	1.01	0.77
B8	33.5	0.48	0.47	0.71	0.63	0.5	0.73	0.46
		Internal Gas Pressures, P_g						
G1	g	56	61	76	90	82	89	--
G3	g	59	56	76	85	--	75	--
G4	g	48	53	70	86	71	87	--

[a] No cover.

[b] $\bar{W}$ = 13.1; $\bar{x}$ = 0.02.

[c] $\bar{W}$ = 13.1; $\bar{x}$ = 0.69.

[d] $\bar{W}$ = 20; $\bar{x}$ = 0.03.

[e] $\bar{W}$ = 20; $\bar{x}$ = 0.44.

[f] $\bar{W}$ = 38.33; $\bar{x}$ = 0.88.

[g] Internal gas pressure gage on wall. Distance not a factor.

Table 5. Scaled Impulse ($W = 13.56$ lb; $W/V = 0.015$ lb/ft^3)

Gage	Scaled Distance, Z (ft/lb$^{1/3}$)	Scaled Impulse (psi-ms/lb$^{1/3}$) for NCEL Test Nos.--						
		6[a]	106[a]	18[b]	19[c]	7[d]	8[e]	9[f]
		External Incident Impulse, $i_s/W^{1/3}$						
F1	4.19	75.30	62.47	28.25	25.99	27.79	27.12	
F2	8.38	30.56	29.18	11.06	10.77	12.49	13.66	
F4	16.8	14.04	14.42	5.19	7.50	5.24	7.21	12.20
F8	33.5	6.24	6.07	2.68	3.22	2.59	3.27	2.68
F12	50.3	3.60	3.64	1.67	2.01	1.71	1.97	1.59
S1	4.19	9.55	10.69	17.23	15.47	16.43	16.10	
S2	8.38	7.92	8.00	11.57	13.87	13.08	12.07	
S4	16.8	3.81	3.56	4.06	3.77	4.19	4.06	3.98
S8	33.5	2.13	2.18	1.97	1.92	2.01	2.01	1.88
D2	8.38	3.56	3.31	4.94	4.19	5.11	4.73	4.73
D4	16.8	2.22	2.18	2.85	2.68	2.85	2.80	
D8	33.5	1.29	1.29	1.59	1.46	1.59	1.59	
B2	8.38	2.09	2.64	3.98	3.60	3.68	3.89	
B3	12.6	2.76	2.47	3.64	3.52	3.94	3.56	
B4	16.8	2.13	2.22	3.22	3.18	3.10	3.27	
B8	33.5	1.25	1.34	1.92	1.84	1.88	1.84	
		Internal Gas Impulse, $i_g/W^{1/3}$						
G1	g	382	411	758	1006	782	1048	--
G3	g	382	361	670	946	--	933	--
G4	g	306	346	675	902	709	925	--

[a] No cover.

[b] $\bar{W} = 13.1$; $\bar{x} = 0.02$.

[c] $\bar{W} = 13.1$; $\bar{x} = 0.69$.

[d] $\bar{W} = 20$; $\bar{x} = 0.03$.

[e] $\bar{W} = 20$; $\bar{x} = 0.44$.

[f] $\bar{W} = 38.33$; $\bar{x} = 0.88$.

[g] Internal gas pressure gage on wall. Distance not a factor.

Table 6. Peak Pressure and Scaled Impulse
($W = 22.6$ lb; $W/V = 0.025$ pcf)

Gage	Scaled Distance, Z (ft/lb$^{1/3}$)	Peak Pressure (psi)	Scaled Impulse (psi-ms/lb$^{1/3}$)
Incident Pressure, P_{so}, and Impulse, $i\ /W^{1/3}$			
F1	3.53	121.3	87.72
F2	7.07	65.7	35.33
F4	14.1	12.5	17.68
F8	28.3	3.47	7.64
F12	42.4	1.76	4.42
S1	3.53	34.6	11.67
S2	7.07	11.8	9.48
S4	14.1	2.04	4.45
S8	28.3	1.13	2.61
D2	7.07	3.5	4.06
D4	14.1	1.37	2.61
D8	28.3	0.56	1.48
B2	7.07	2.36	3.11
B3	10.6	1.92	3.32
B4	14.1	1.26	2.75
B8	28.3	0.93	1.69
Gas Pressure, P_g, and Impulse, $i_g/W^{1/3}$			
G1	b	86	532
G3	b	65	482
G4	b	66	392

[a] $\bar{w} = 0$; $\bar{x} = 0$.

[b] Internal gas pressure gage on wall. Distance not a factor.

Table 7. Peak Pressure (W = 40.7 lb; W/V = 0.045 pcf)

Gage	Scaled Distance, Z (ft/lb$^{1/3}$)	Peak Pressures (psi) for NCEL Test Nos.—					
		10[a]	11[b]	12[c]	13[d]	14[e]	17[f]
		External Incident Pressures, P_{so}					
F1	2.91	182.0	45.3	41.1	48.5	26.2	30.9
F2	5.81	72.8	18.6	13.3	14.2	15.8	16.0
F4	11.6	17.5	6.04	5.53	5.22	6.22	6.37
F8	23.3	4.36	2.54	2.51	2.19	1.91	1.45
F12	34.9	2.37	1.44	1.57	1.34	1.07	0.71
S1	2.91	40.3	26.9	30.3	22.5	25.2	14.9
S2	5.81	15.9	26.8	21.2	23.3	16.2	12.1
S4	11.6	3.03	5.11	4.24	2.56	3.91	4.26
S8	23.3	1.53	2.64	2.39	1.96	1.81	3.06
D2	5.81	5.66	8.83	5.01	5.24	5.75	3.39
D4	11.6	1.99	3.24	2.33	2.86	2.35	2.47
D8	23.3	0.97	1.32	1.18	1.2	1.33	1.07
B2	5.81	4.11	6.96	3.33	3.55	3.13	2.85
B3	8.72	2.57	3.79	1.82	2.16	2.02	1.8
B4	11.6	1.47	2.56	1.66	1.51	1.43	1.48
B8	23.3	0.98	1.73	1.35	1.13	1.74	0.93
		Internal Gas Pressures, P_g					
G1	[g]	103	140	172	161	218	—
G3	[g]	92	—	140	137	199	194
G4	[g]	102	148	148	146	173	185

[a] No cover.

[b] $\bar{w}$ = 9.08; $\bar{x}$ = 0.01.

[c] $\bar{w}$ = 9.08; $\bar{x}$ = 0.48.

[d] $\bar{w}$ = 67.2; $\bar{x}$ = 0.03.

[e] $\bar{w}$ = 67.2; $\bar{x}$ = 0.48.

[f] $\bar{w}$ = 134; $\bar{x}$ = 0.48.

[g] Internal gas pressure gage on wall. Distance not a factor.

Table 8. Scaled Impulse (W = 40.7 lb; W/V = 0.045 pcf)

Gage	Scaled Distance, Z ($ft/lb^{1/3}$)	Scaled Impulse ($psi\text{-}ms/lb^{1/3}$) for NCEL Test Nos.-- 10[a]	11[b]	12[c]	13[d]	14[e]	17[f]
		External Incident Impulse, $i_s/W^{1/3}$					
F1	2.91		54.06	57.55	27.64		19.47
F2	5.81	35.17	17.76	17.58	12.73	16.65	10.02
F4	11.6	22.38	10.29	11.33	7.81	10.66	9.30
F8	23.3	9.09	5.52	6.01	4.47	5.43	4.53
F12	34.9	5.61	3.45	4.04	2.90	3.25	2.84
S1	2.91	12.52	14.33	14.21	15.29	13.69	13.72
S2	5.81	8.72	18.72	16.16	17.09	14.73	14.56
S4	11.6	5.05	2.47	5.43	6.39	5.98	6.25
S8	23.3	2.73	2.93	2.79	2.99	3.02	4.18
D2	5.81	10.05	6.97	6.42	6.54	5.90	5.63
D4	11.6	3.19	4.21	3.98	4.30	3.77	3.66
D8	23.3	1.91	2.20	2.18	2.44	3.54	2.12
B2	5.81	3.83	5.52	5.14	4.82	4.44	4.30
B3	8.72	4.15	5.84	4.97	4.68	4.30	4.18
B4	11.6	2.84	4.91	4.41	4.15	3.92	3.69
B8	23.3	1.94	2.79	2.67	2.50	2.41	2.32
		Internal Gas Impulse, $i_g/W^{1/3}$					
G1	g	671	997	1345	1171	1581	—
G3	g	510	—	1052	996	1343	1630
G4	g	435	814	1044	1024	1364	1611

[a] No cover.

[b] $\bar{w}$ = 9.08; $\bar{x}$ = 0.01.

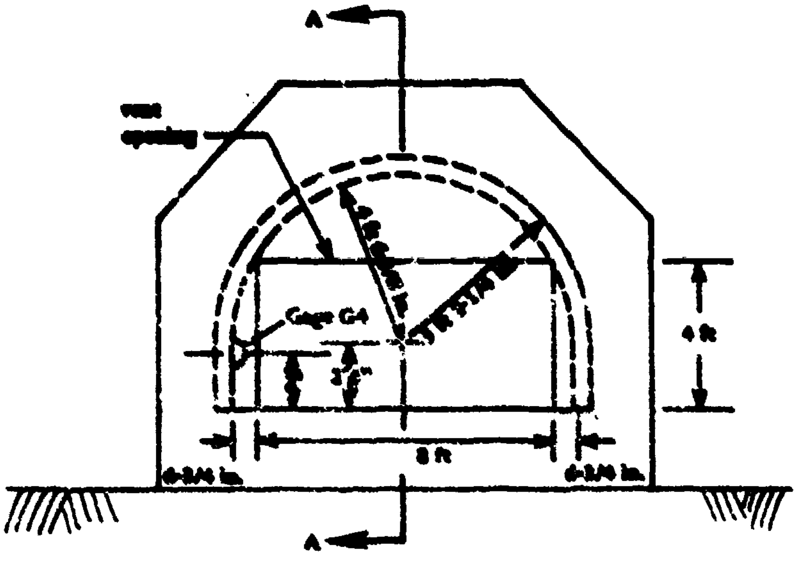
[c] $\bar{w}$ = 9.08; $\bar{x}$ = 0.48.

[d] $\bar{w}$ = 67.2; $\bar{x}$ = 0.03.

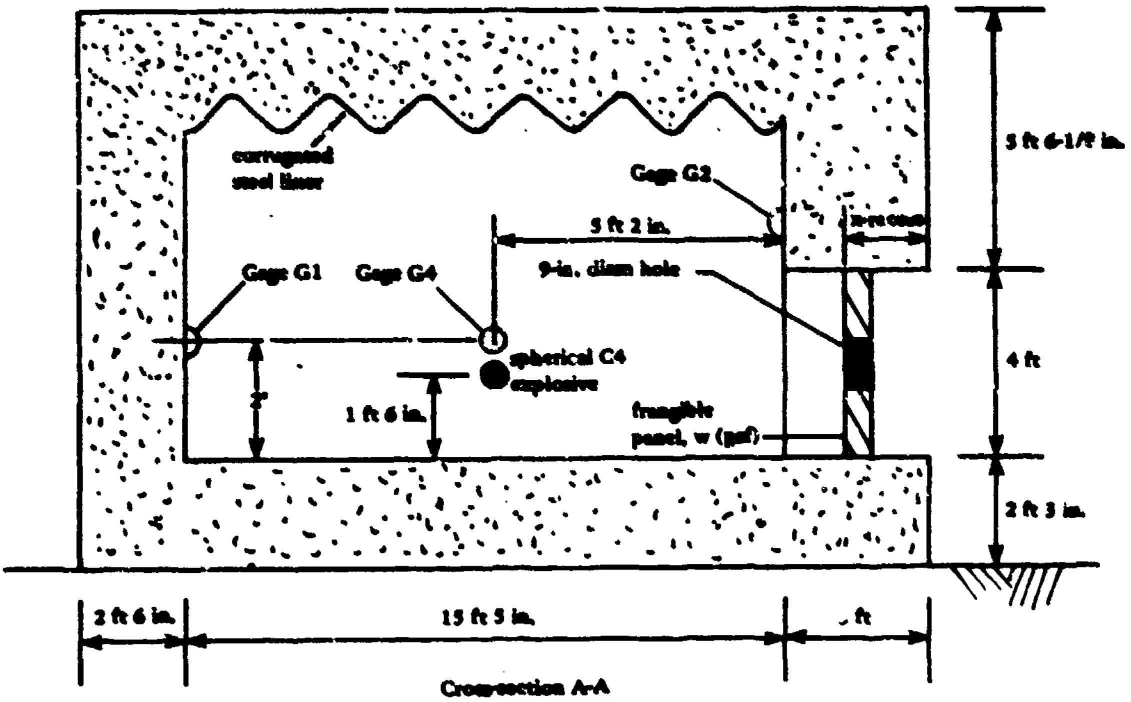
[e] $\bar{w}$ = 67.2; $\bar{x}$ = 0.48.

[f] $\bar{w}$ = 134; $\bar{x}$ = 0.48.

[g] Internal gas pressure gage on wall. Distance not a factor.



Front View



Cross-section A-A

Figure 1. Scale model missile test cell.

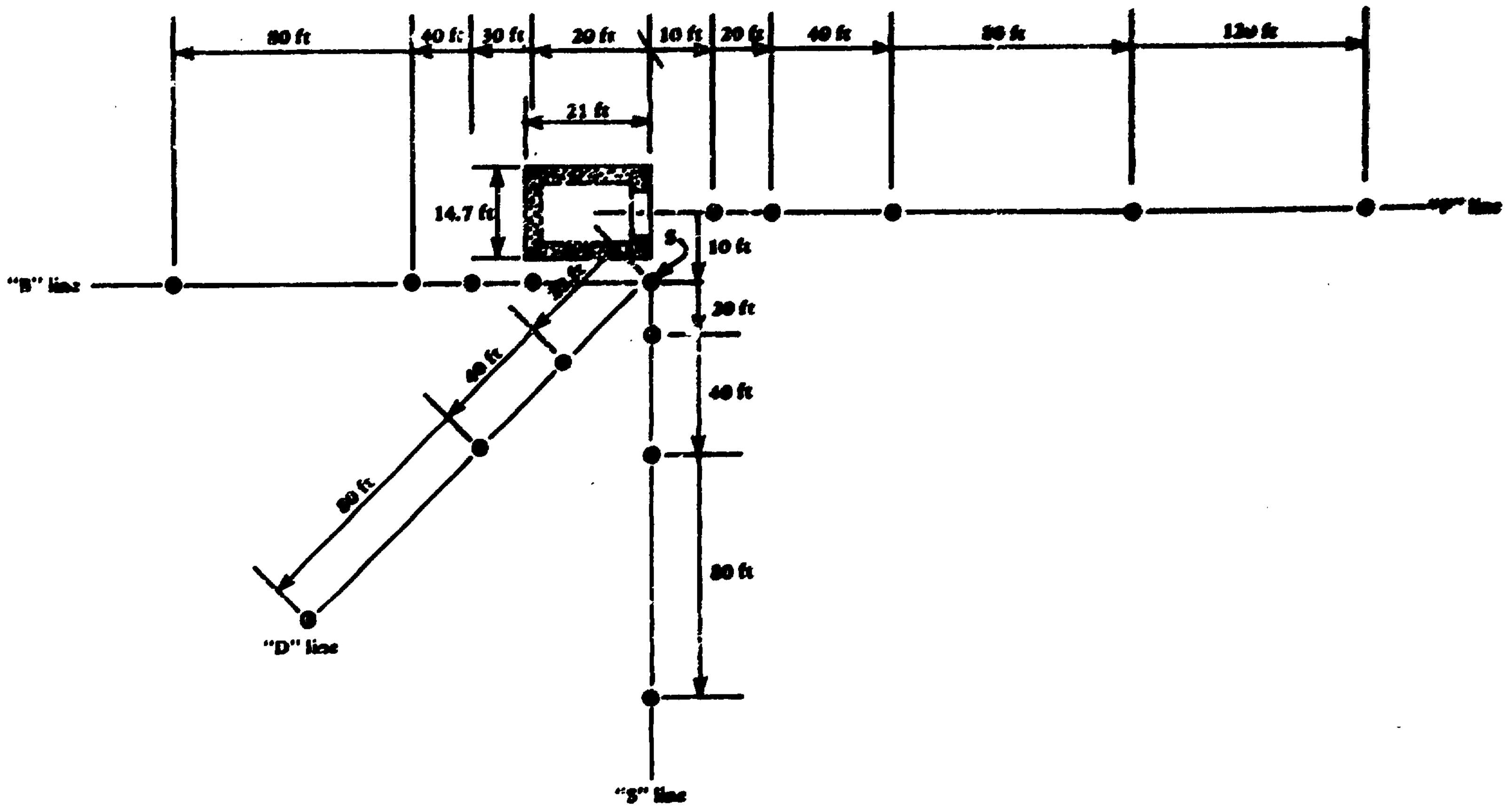


Figure 2. External pressure gage locations.

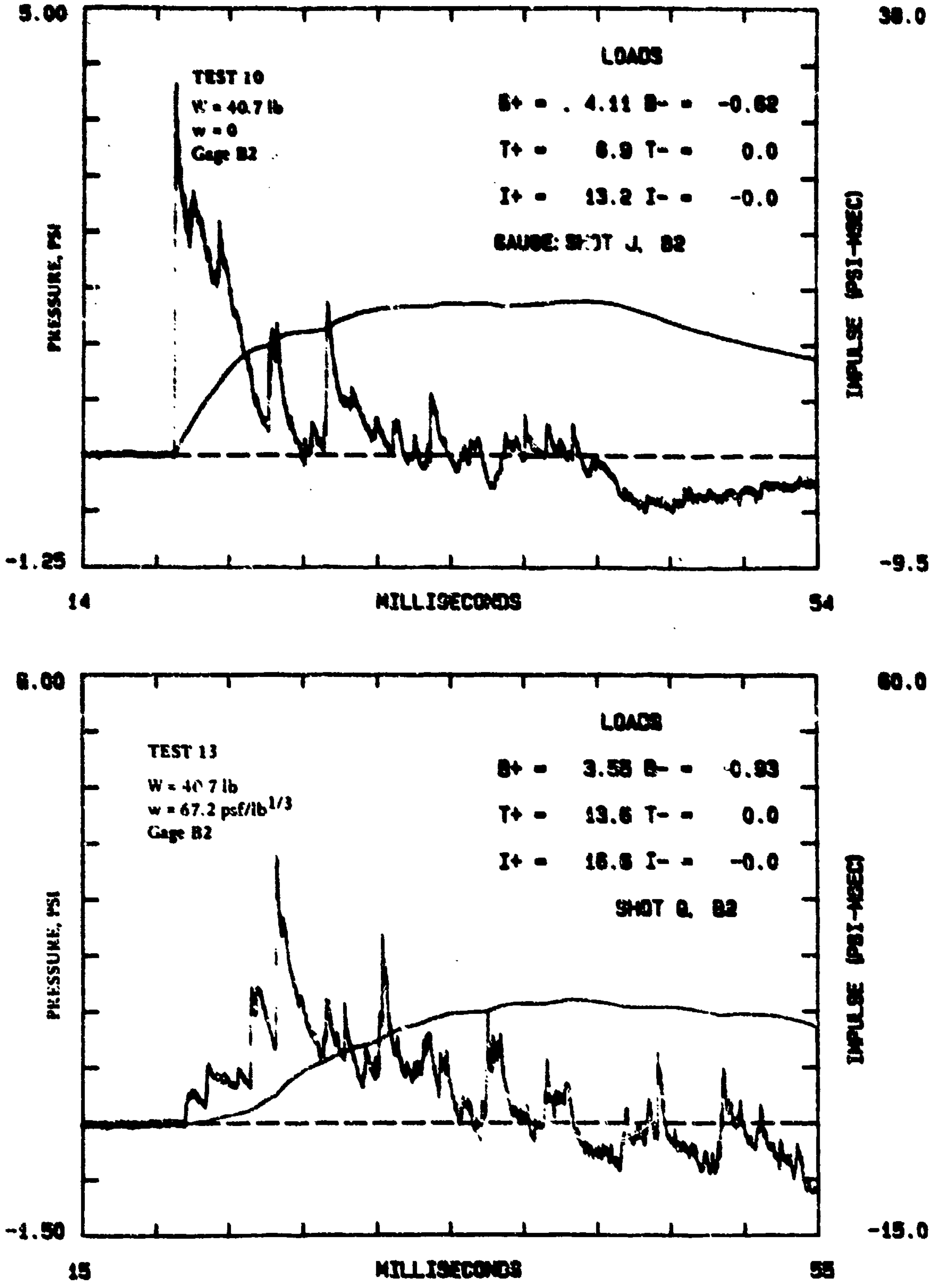


Figure 3. Sample pressure time histories, w = 40.7 lb, with and without vent cover.

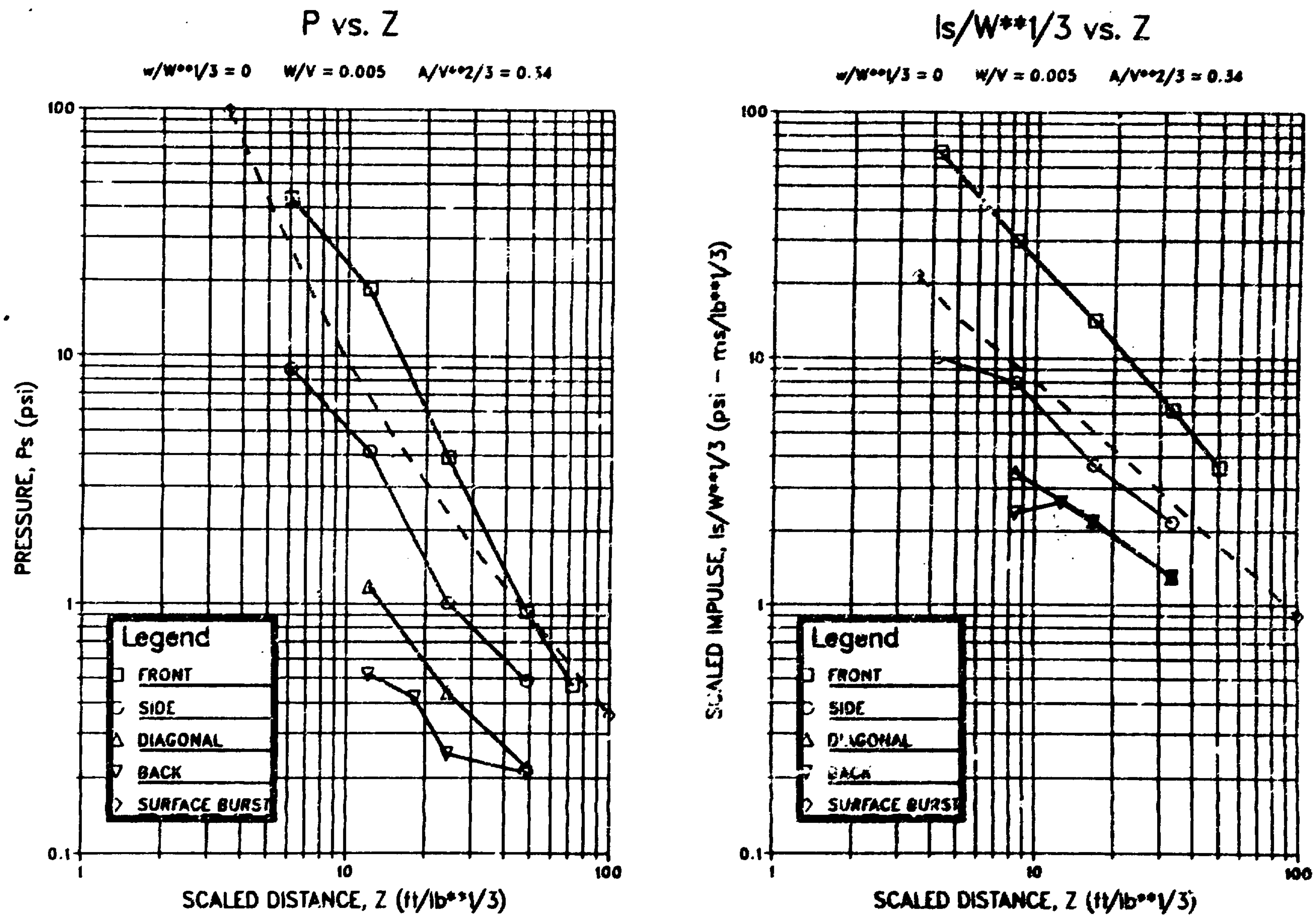


Figure 4. Blast environment vs. direction for $W/V = 0.005\ lb/ft^3$ and $w/W^{1/3} = 0$.

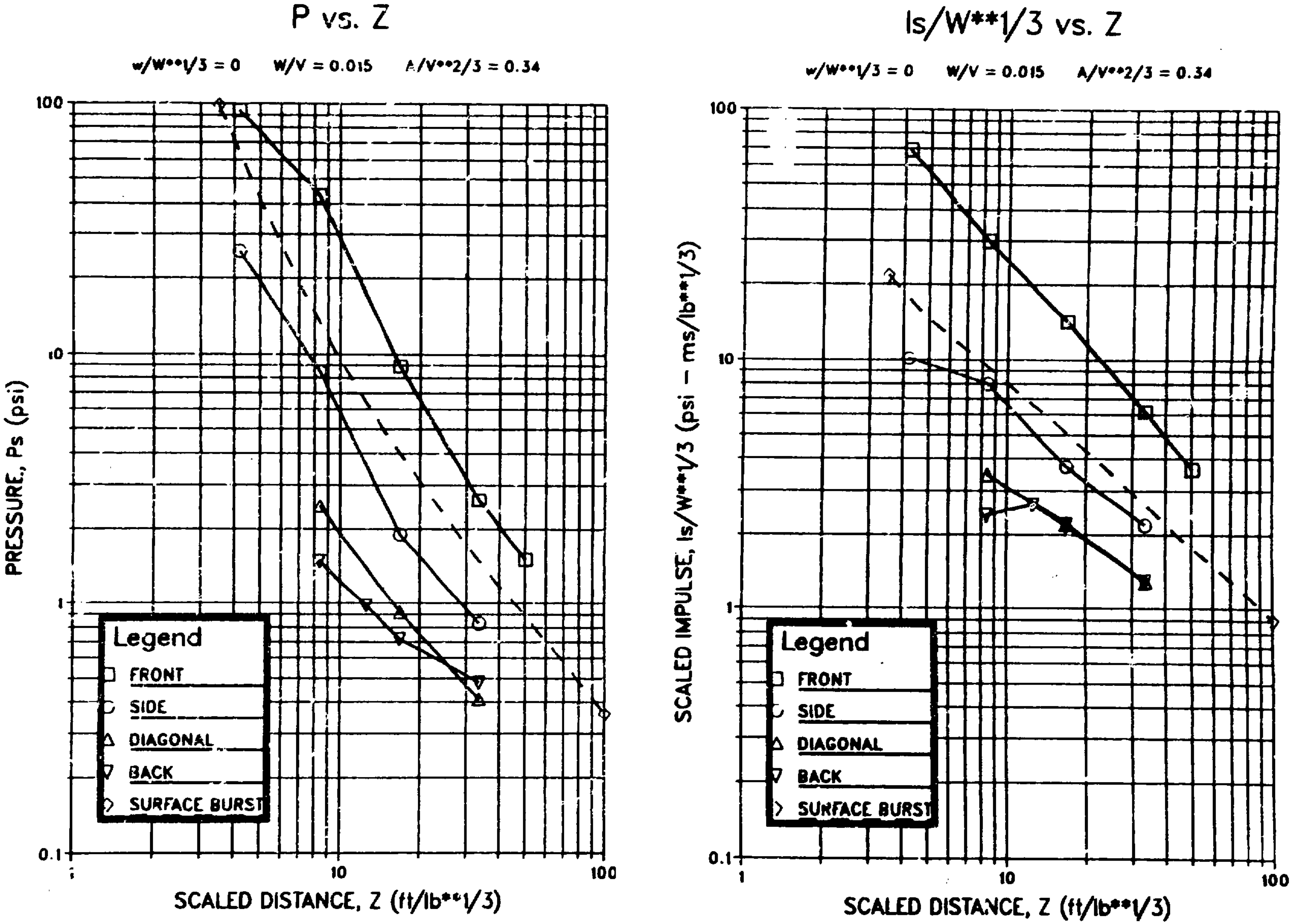


Figure 5. Blast environment vs. direction for $W/V = 0.015\ lb/ft^3$ and $w/W^{1/3} = 0$.

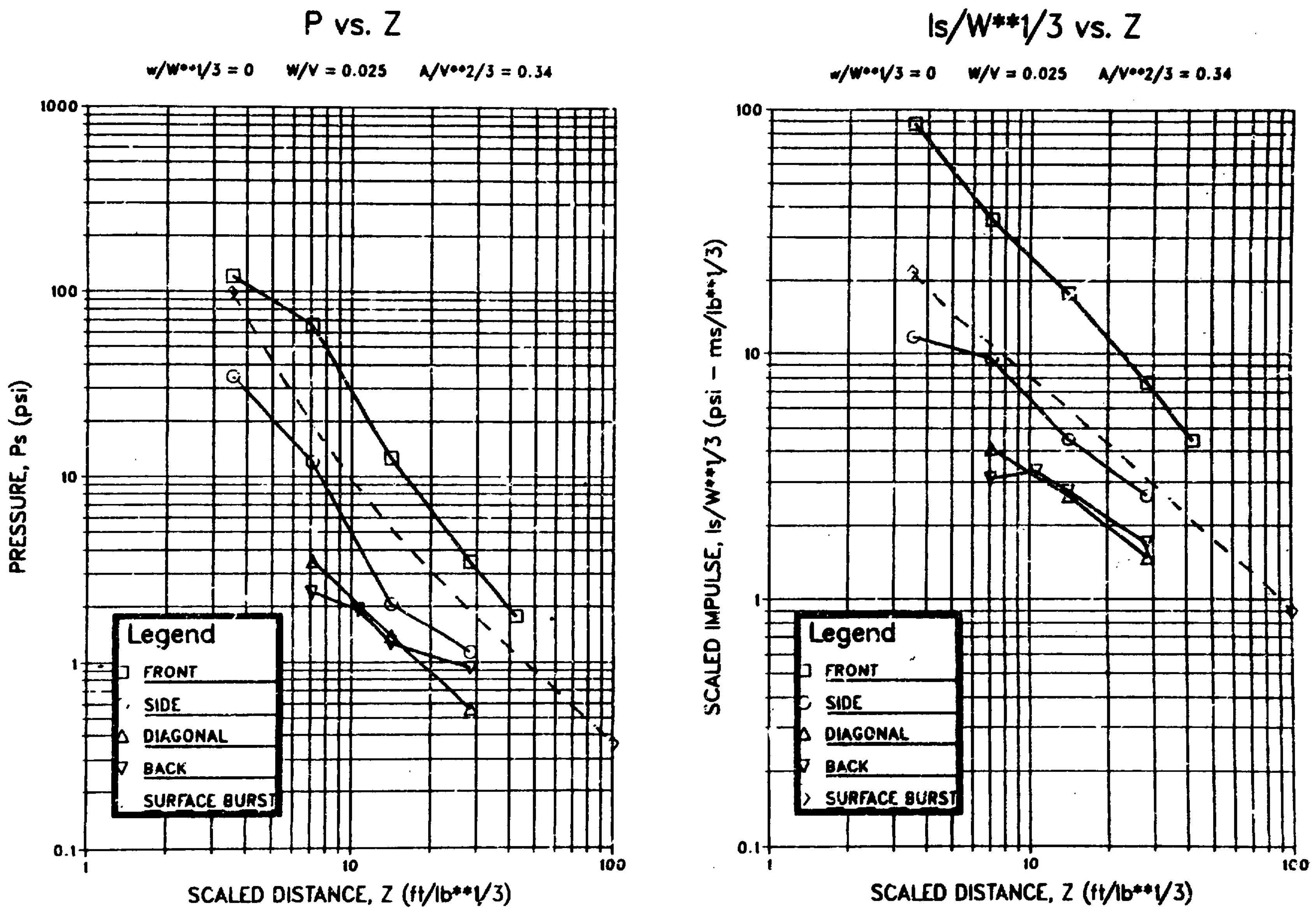


Figure 6. Blast environment vs. direction for W/V = 0.025 lb/ft^3 and w/W$^{1/3}$ = 0.

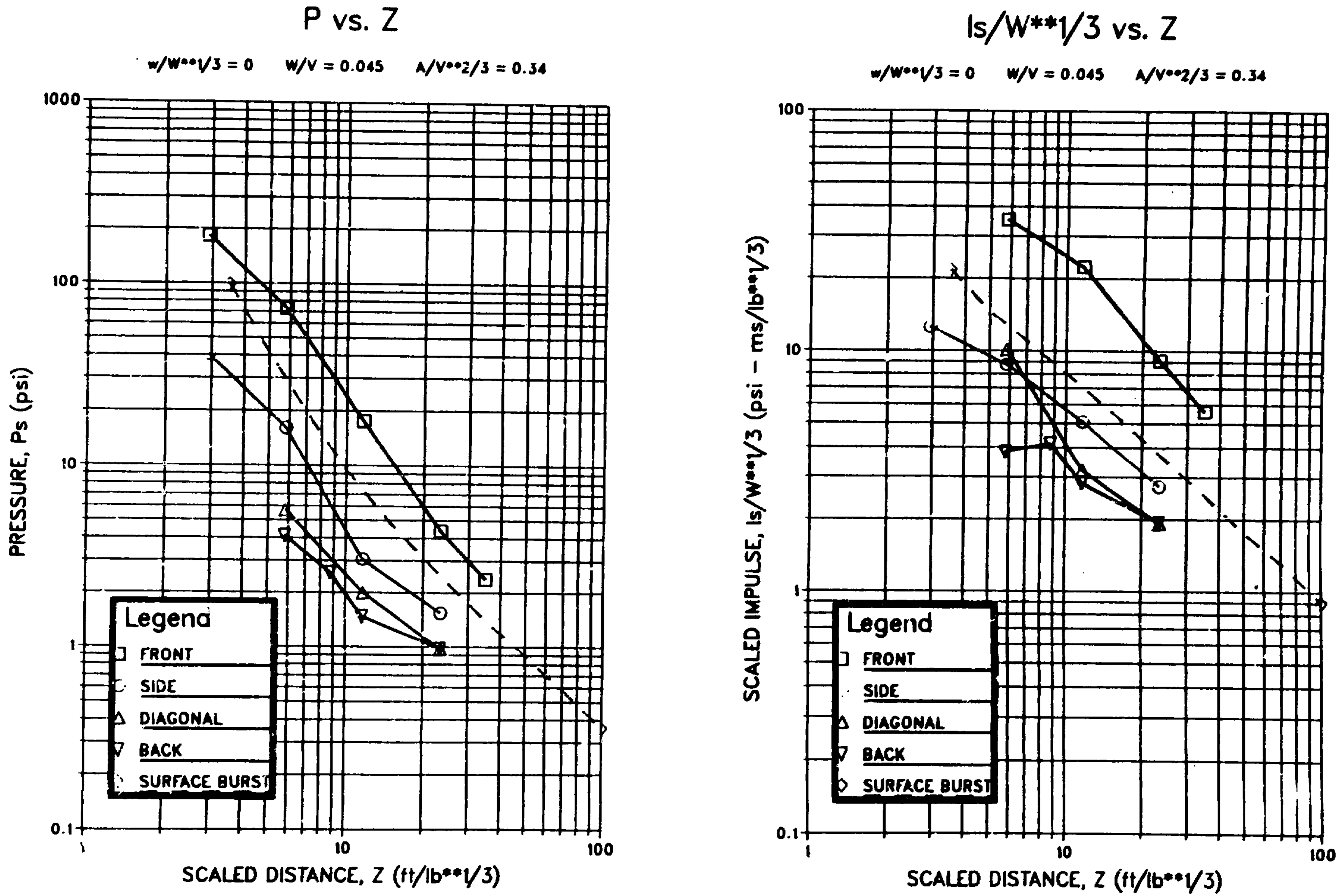


Figure 7. Blast environment vs. direction for $W/V = 0.045$ lb/ft^3 and $w/W^{1/3} = 0$.

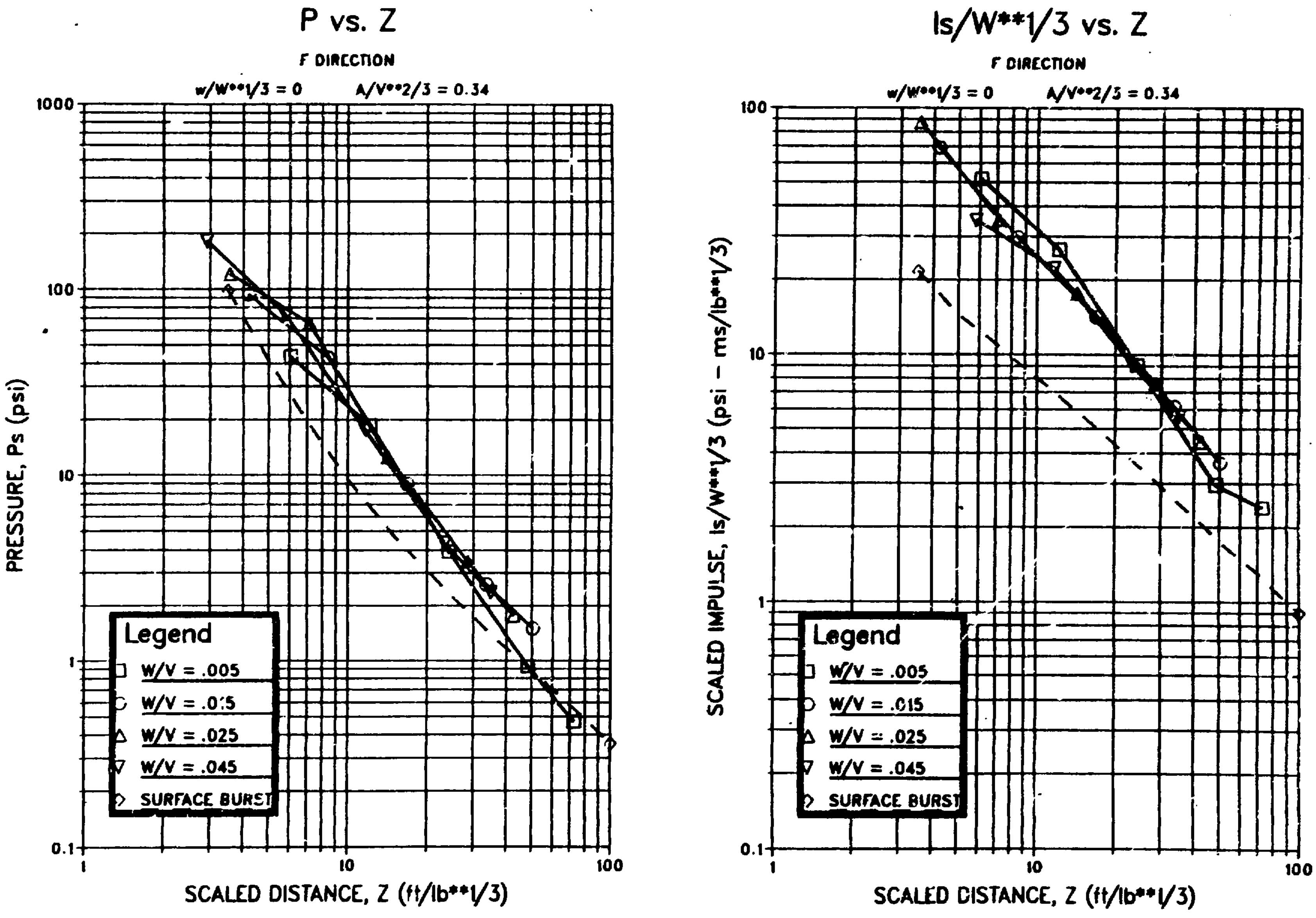


Figure 8. Blast environment vs. W/V for "F" direction and $w/W^{1/3} = 0$.

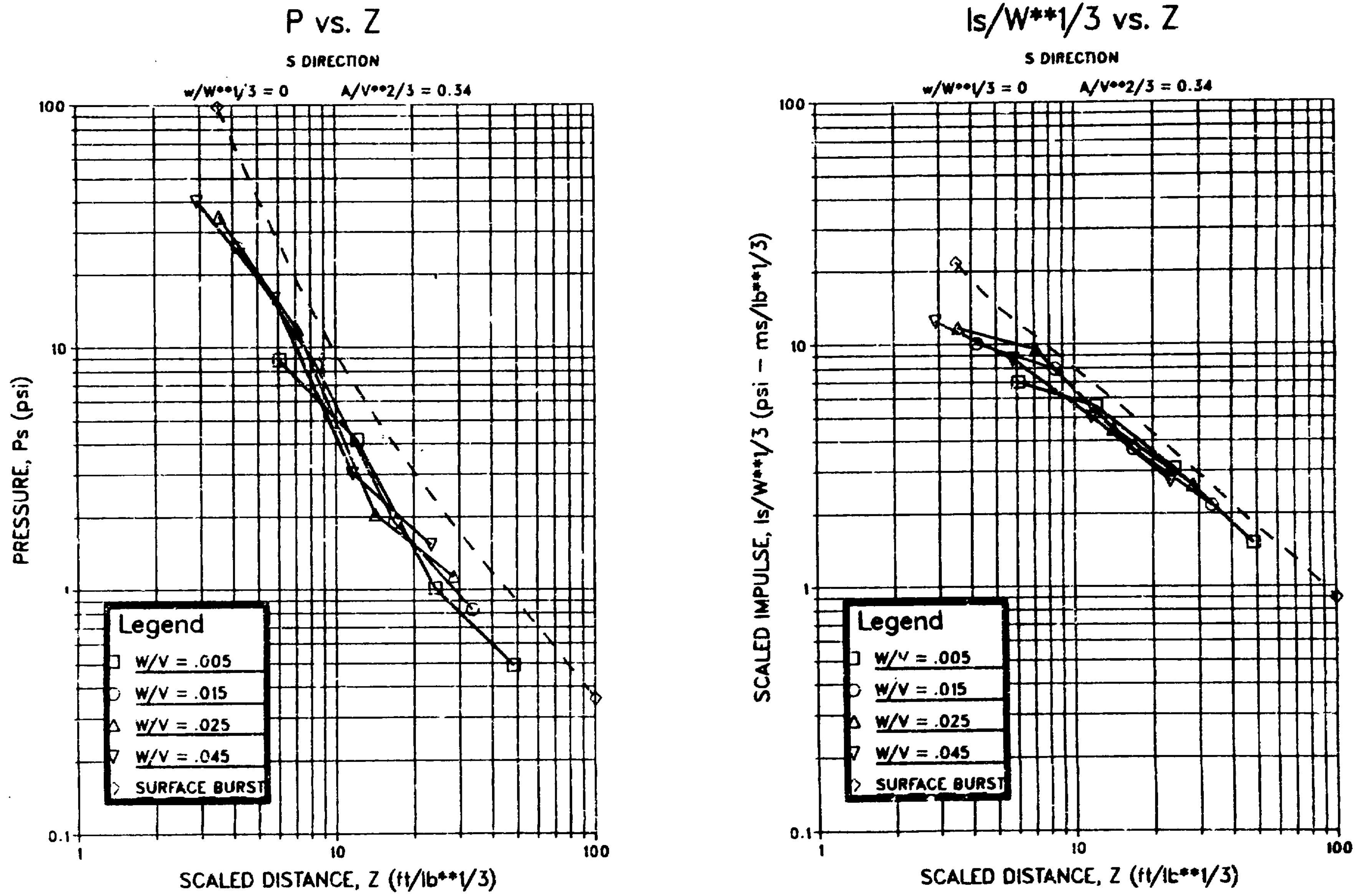


Figure 9. Blast environment vs. W/V for "S" direction and $w/W^{1/3} = 0$.

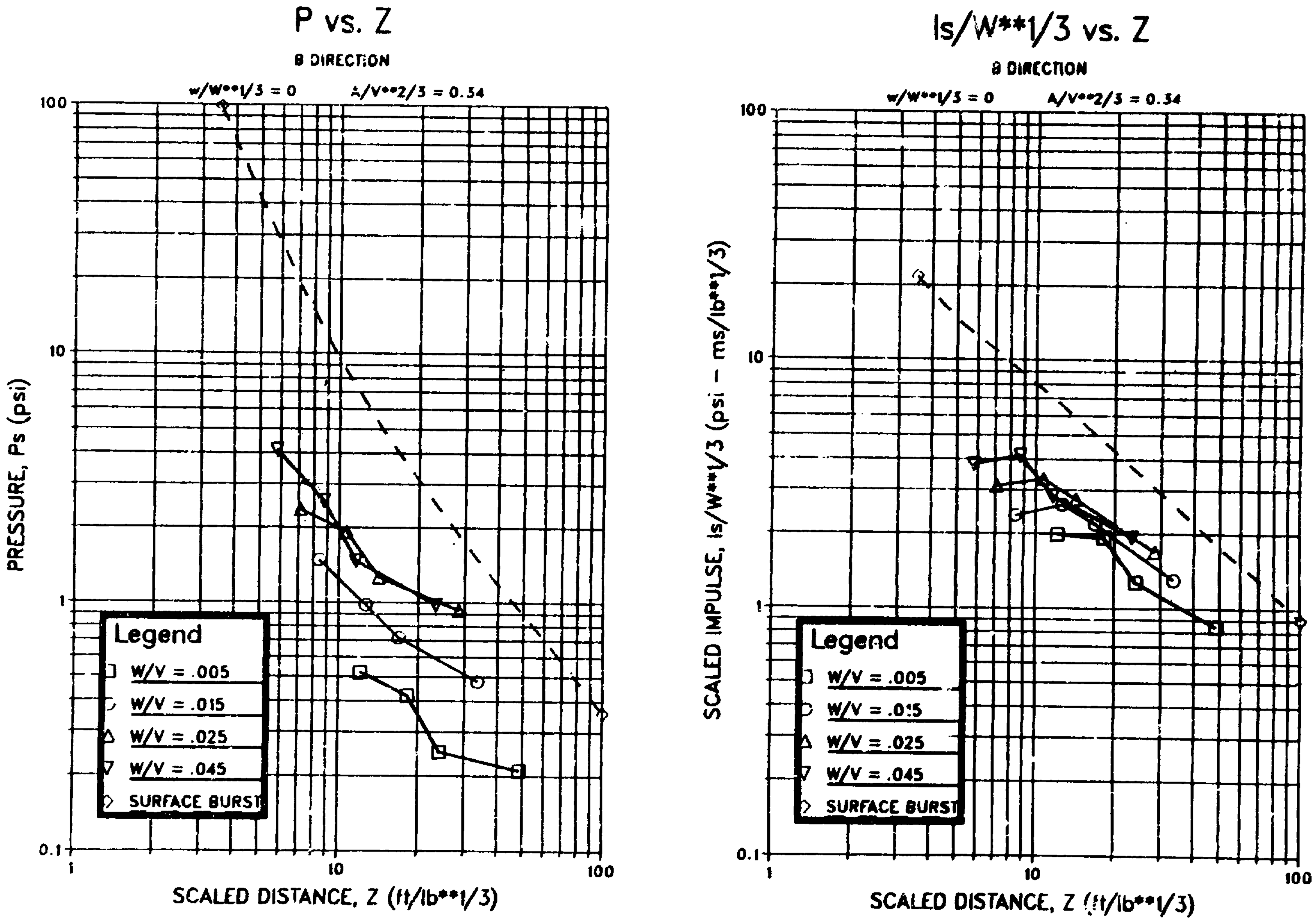


Figure 10. Blast environment vs. W/V for "B" direction and $w/W^{1/3} = 0$.

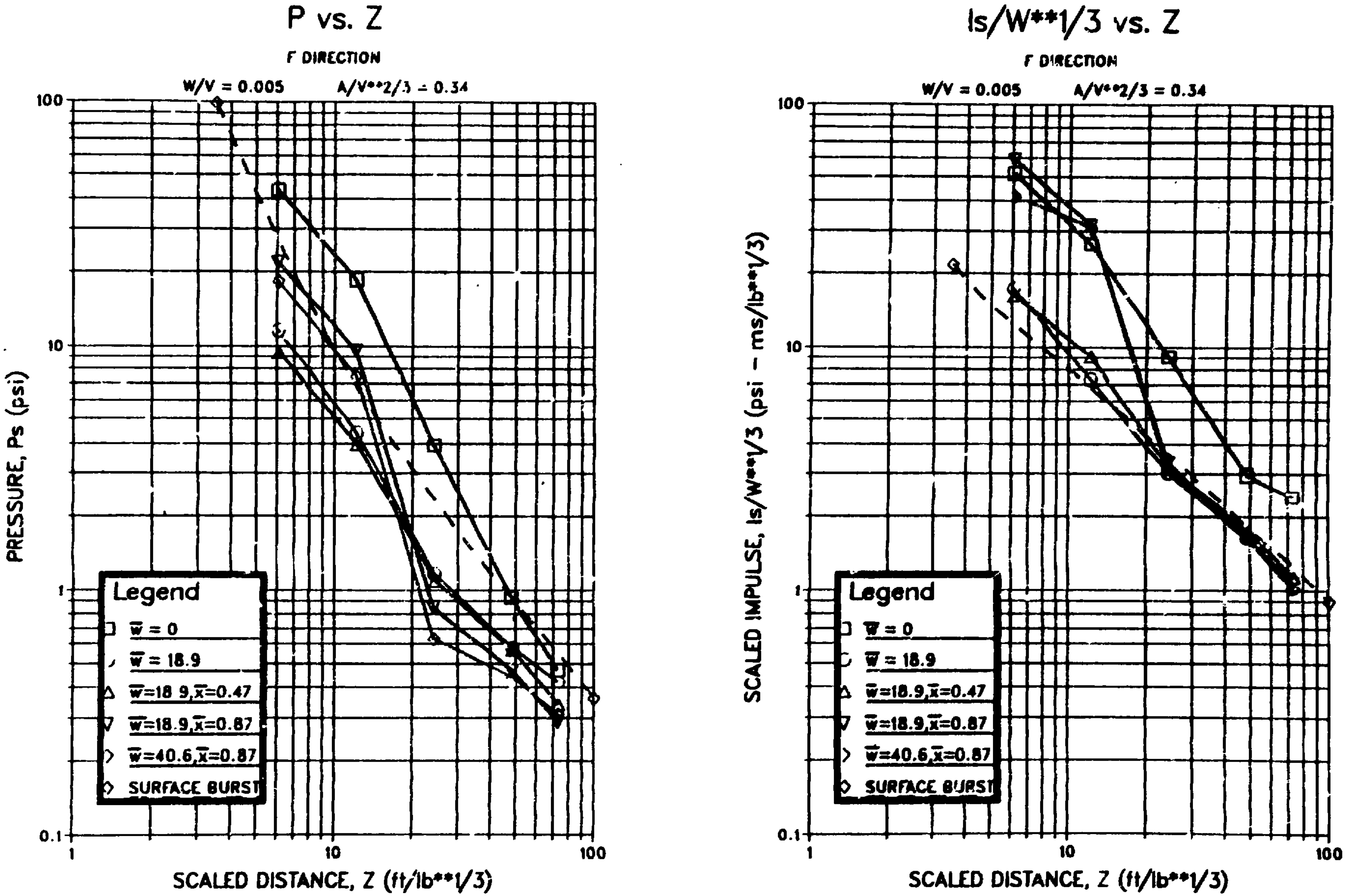


Figure 11. Blast environment vs. $w/W^{1/3}$ and $x/W^{1/3}$ in "F" direction for $W/V = 0.005$ lb/ft^3.

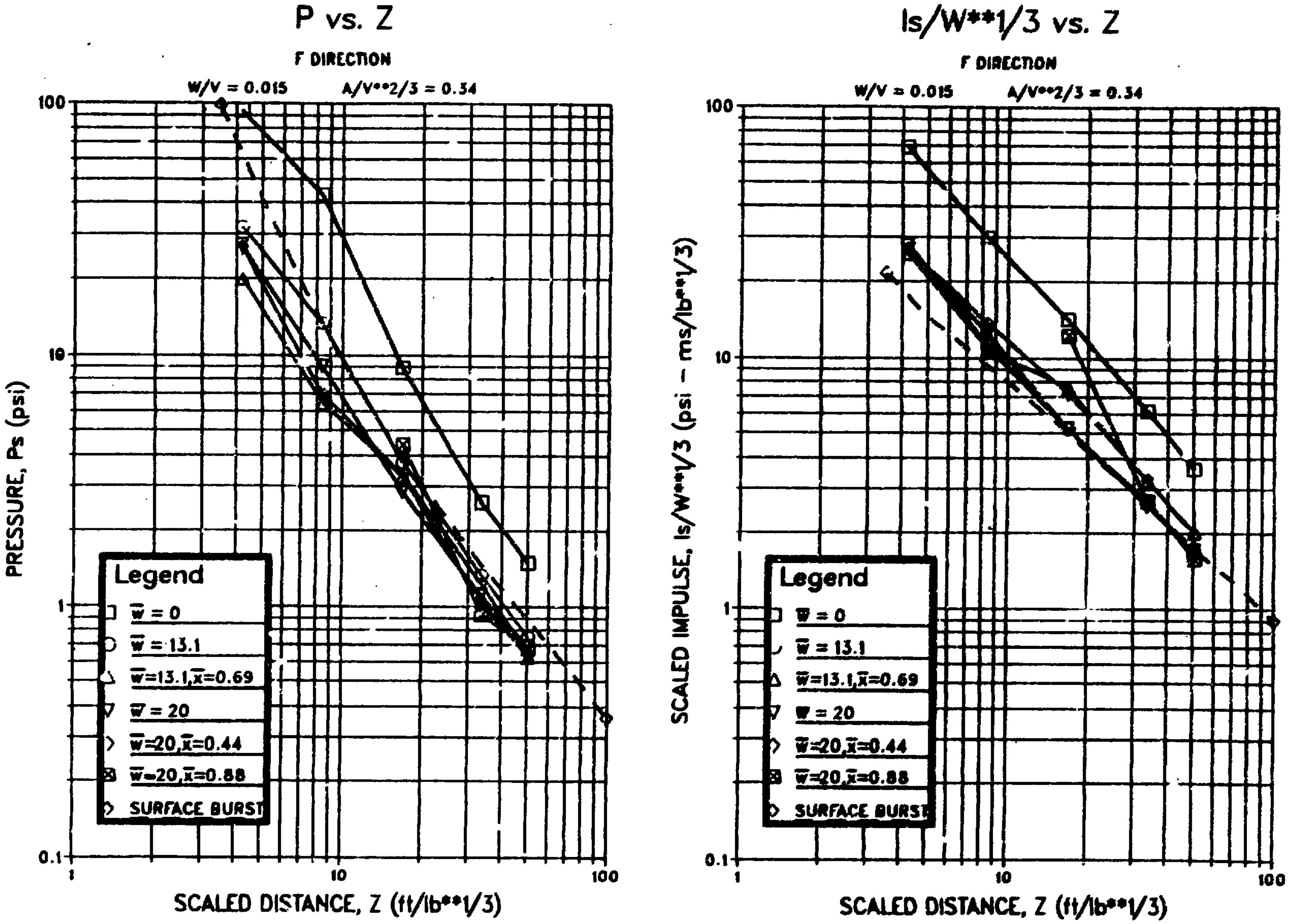


Figure 12. Blast environment vs. $w/W^{1/3}$ and $x/W^{1/3}$ in "F" direction for W/V = 0.015 lb/ft^3.

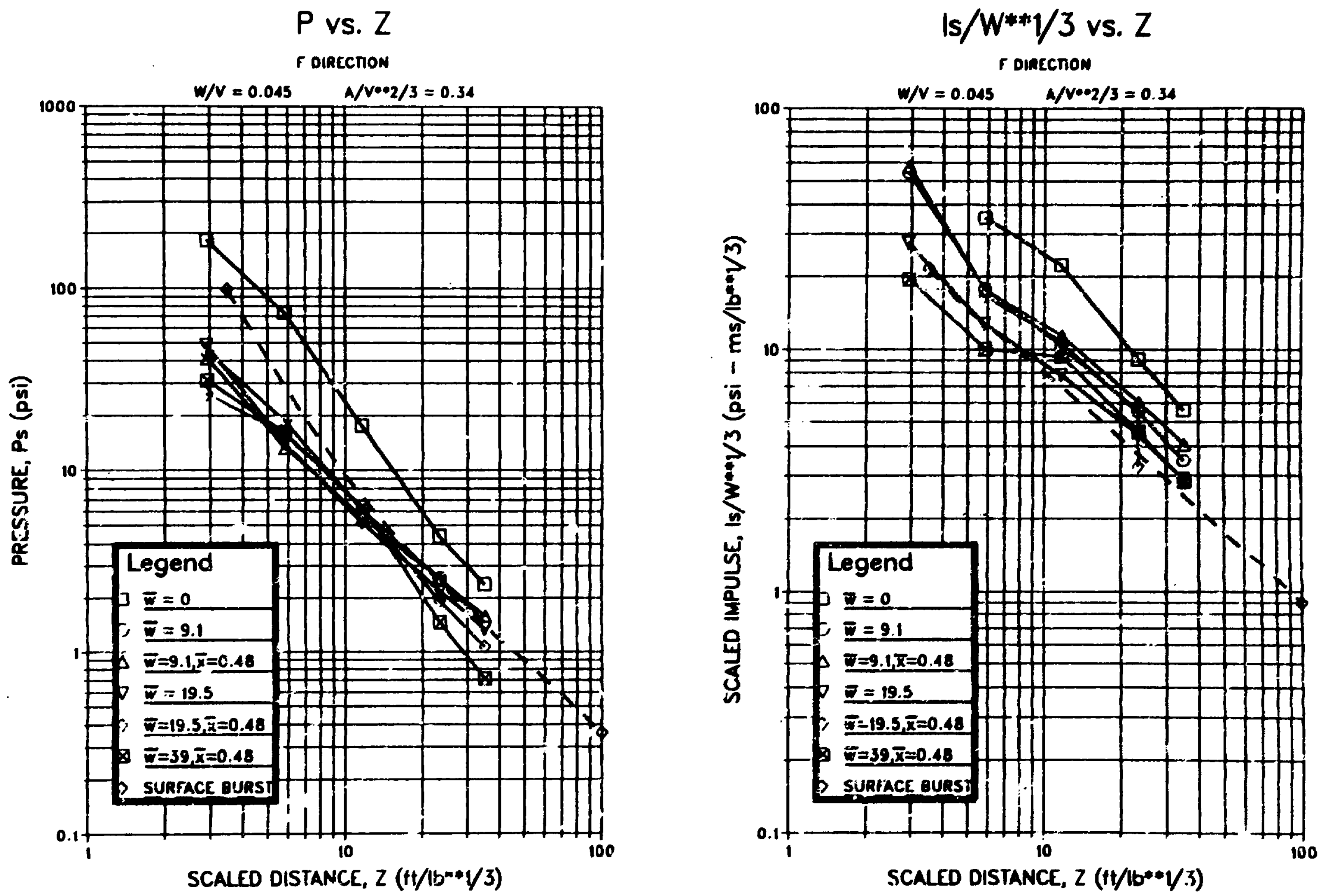
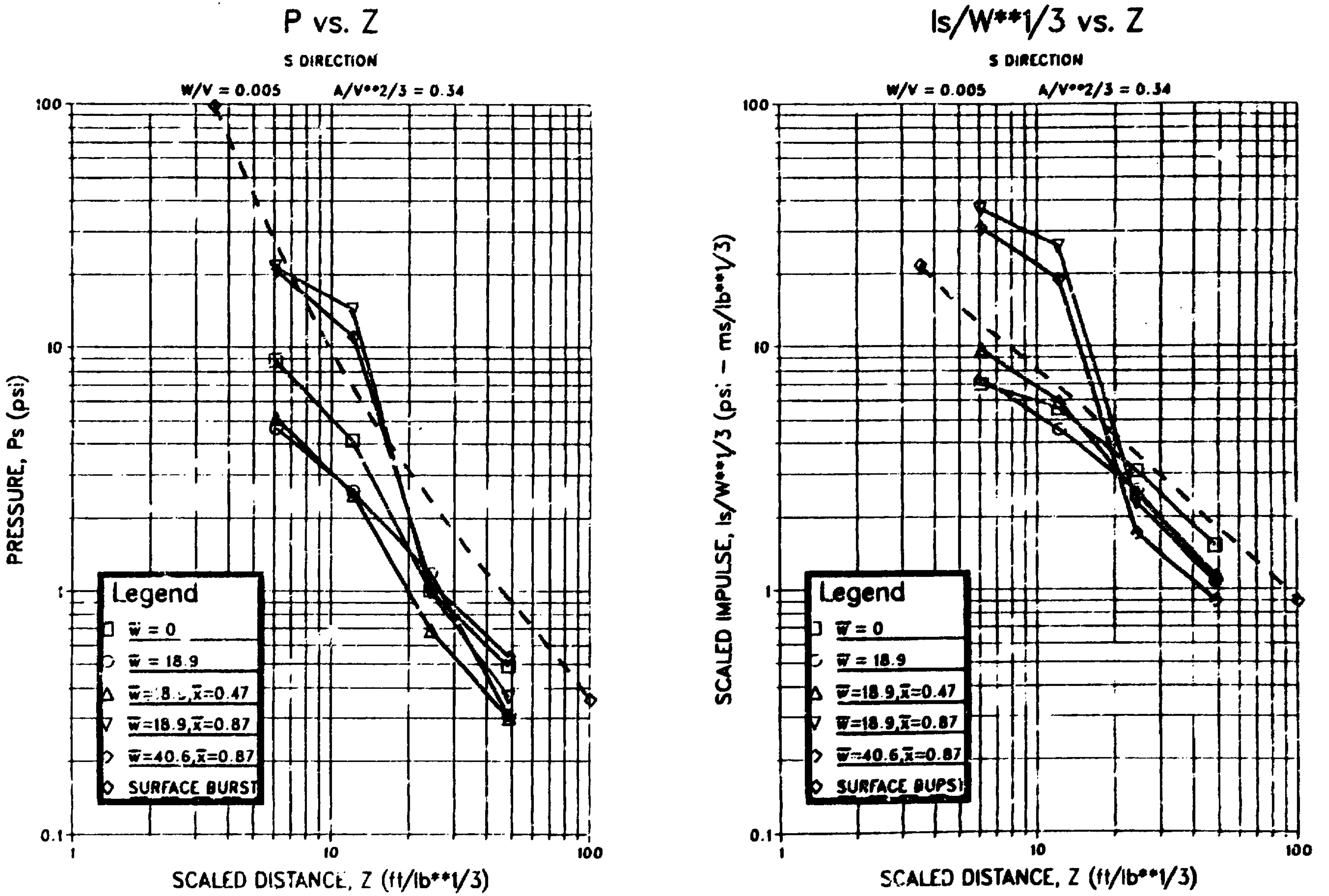


Figure 13. Blast environment vs. $w/W^{1/3}$ and $x/W^{1/3}$ in "F" direction for $W/V = 0.045$ lb/ft^3.



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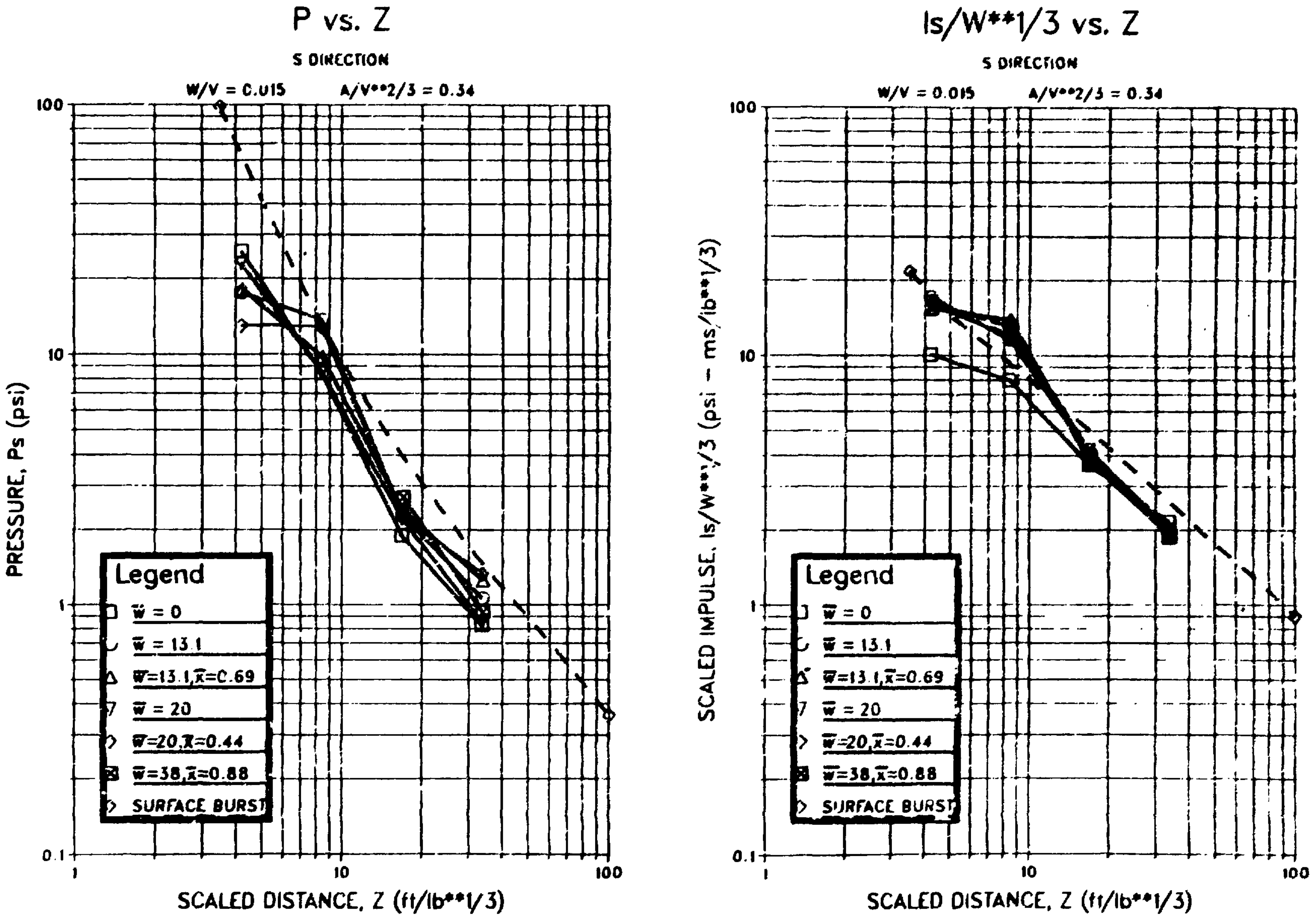

Figure 15. Blast environment vs. $w/W^{1/3}$ and $x/W^{1/3}$ in "S" direction for $W/V = 0.015$ lb/ft^3.

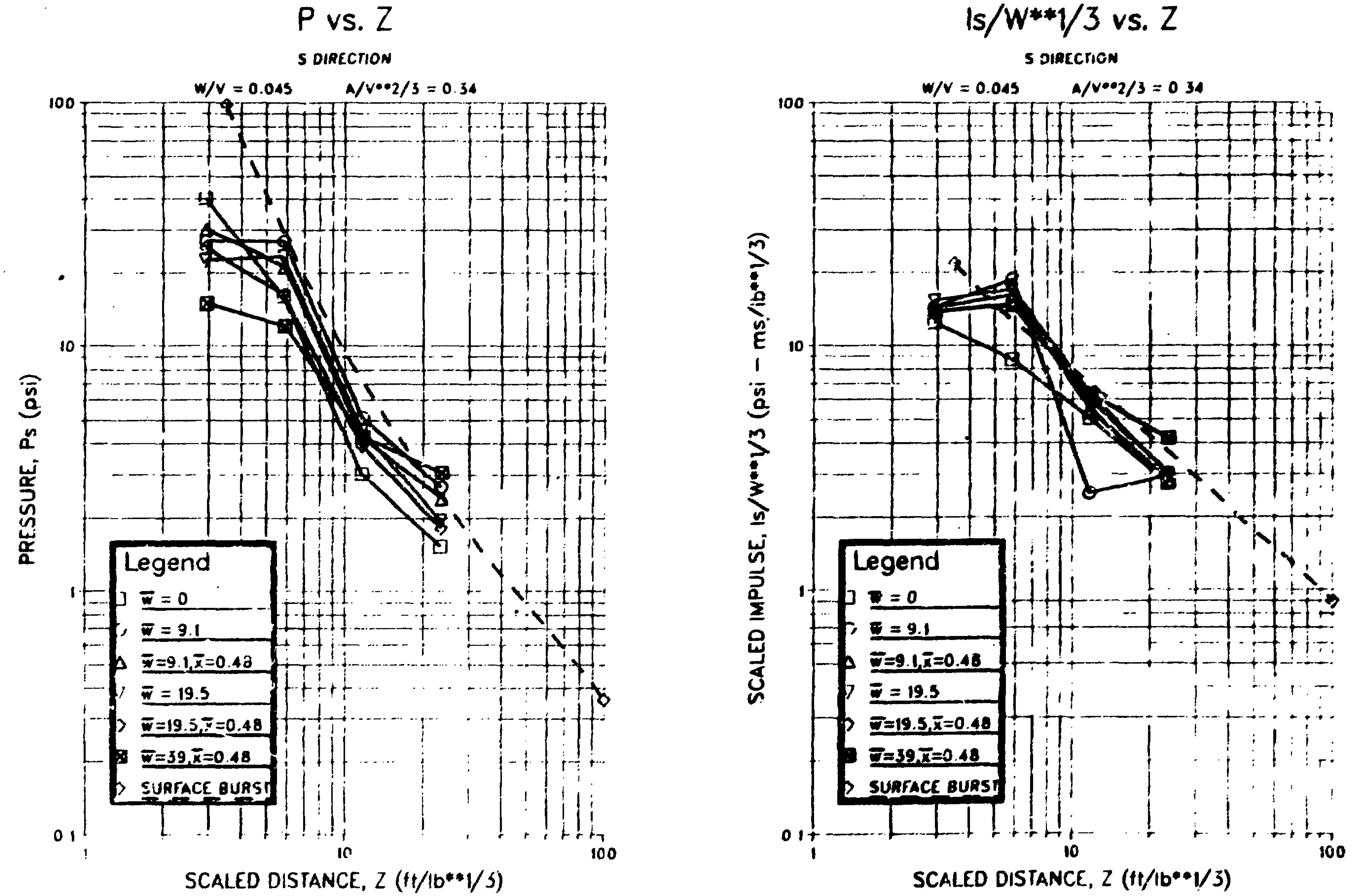

Figure 16. Blast environment vs. $w/W^{1/3}$ and $x/W^{1/3}$ in "S" direction for $W/V = 0.045$ lb/ft^3.

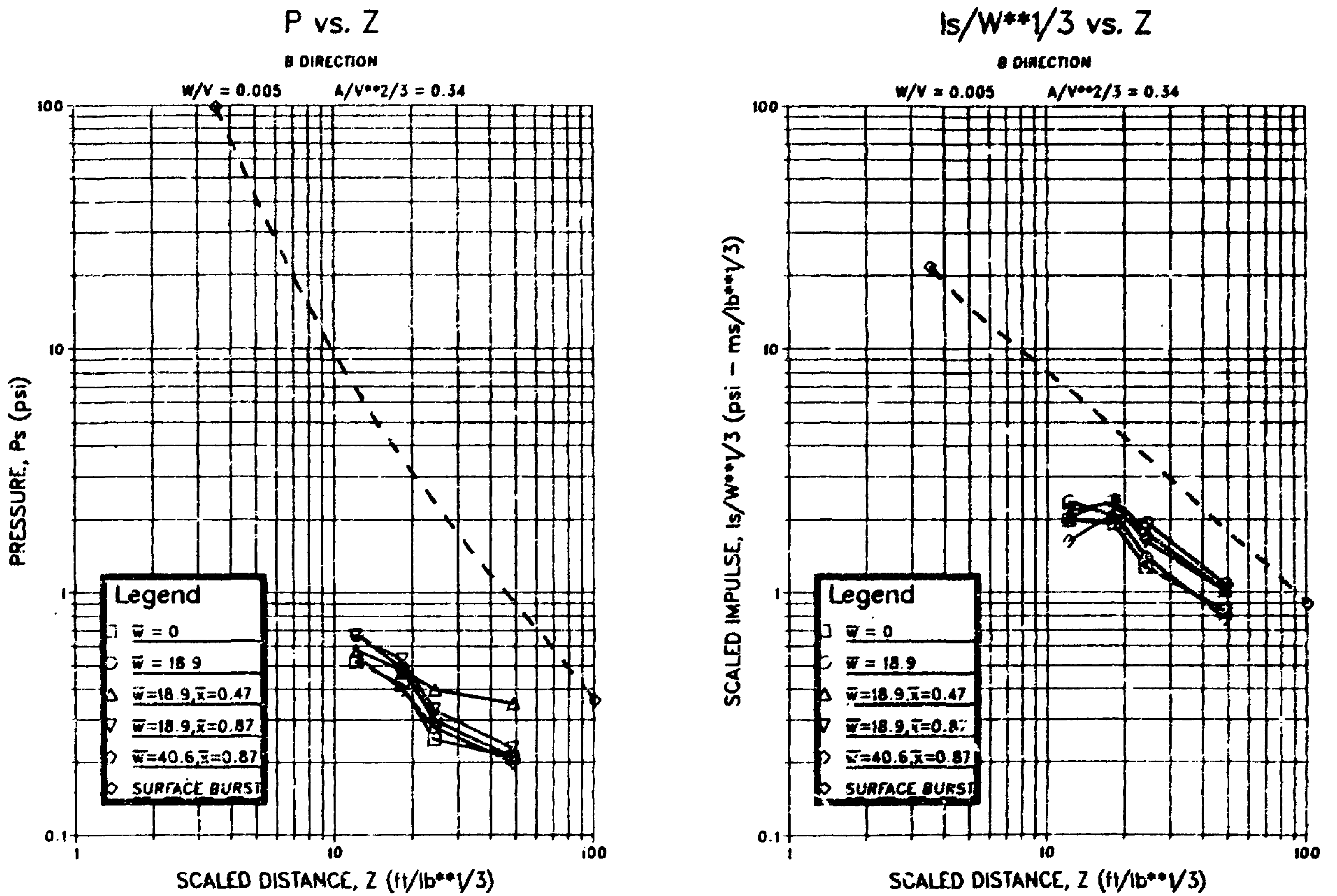

Figure 17. Blast environment vs. $w/W^{1/3}$ and $x/W^{1/3}$ in "B" direction for $W/V = 0.005$ lb/ft^3.

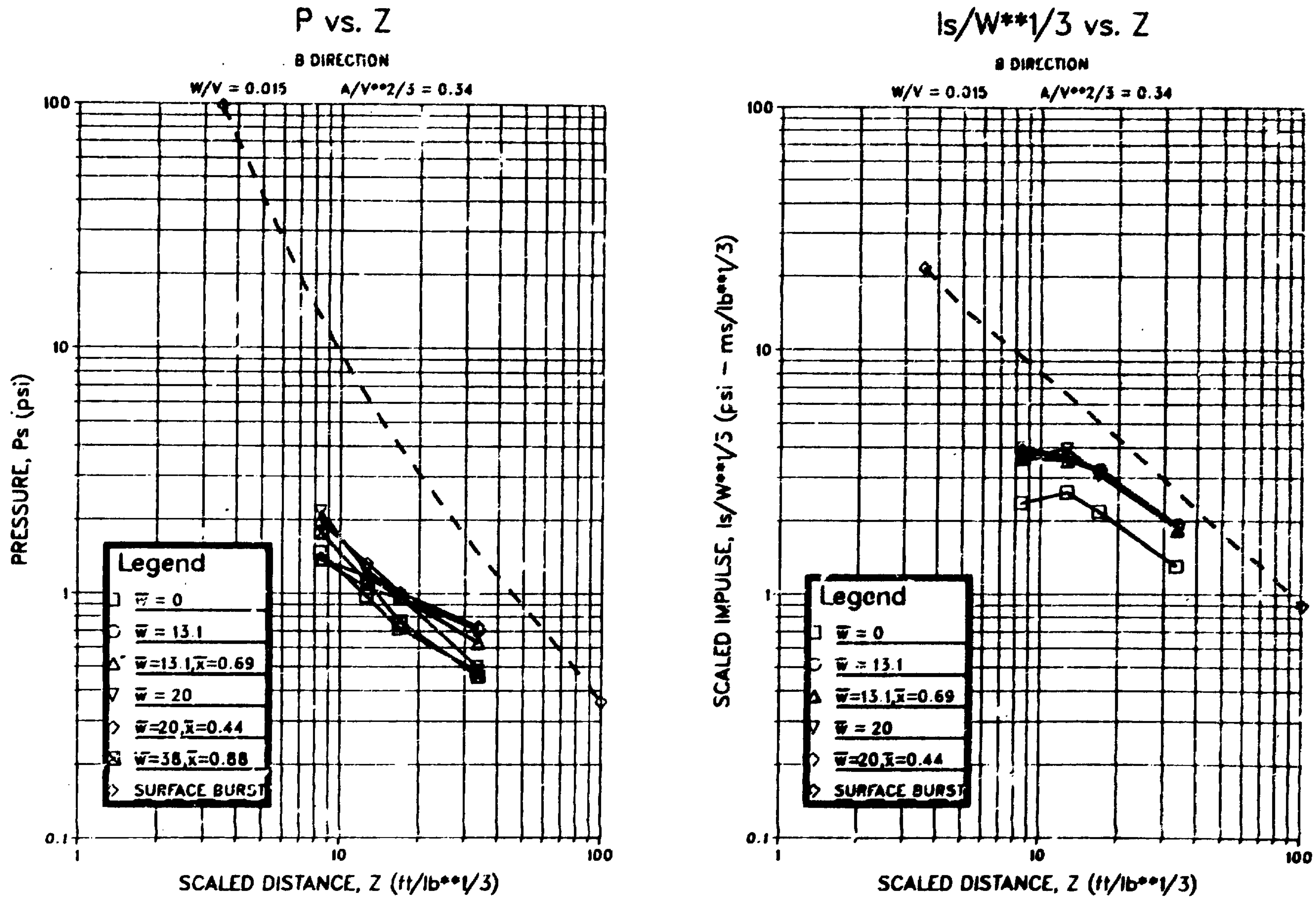

Figure 18. Blast environment vs. $w/W^{1/3}$ and $x/W^{1/3}$ in "B" direction for $W/V = 0.015\ lb/ft^3$.

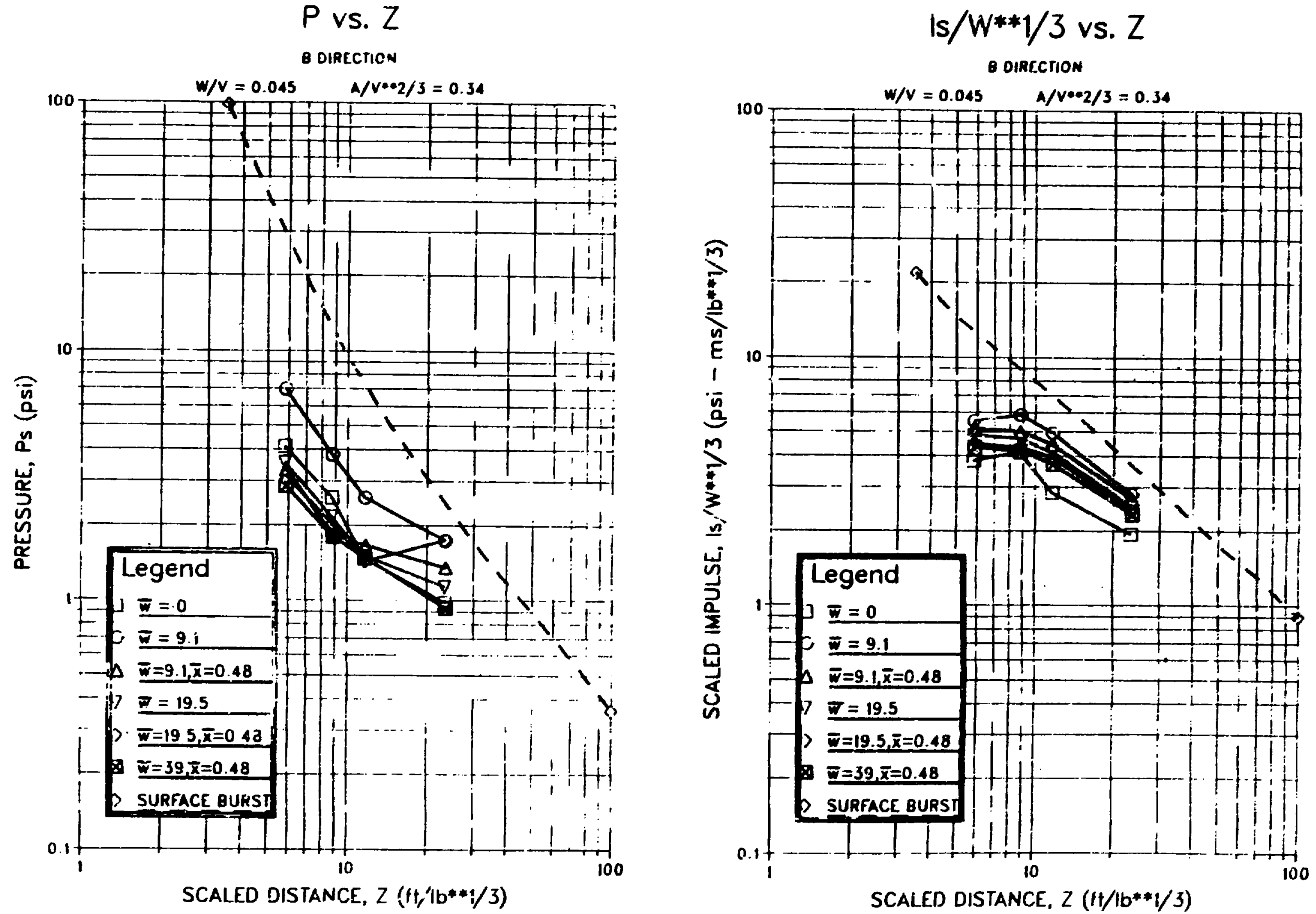

Figure 19. Blast environment vs. $w/W^{1/3}$ and $x/W^{1/3}$ in "B" direction for $W/V = 0.045$ lb/ft^3.

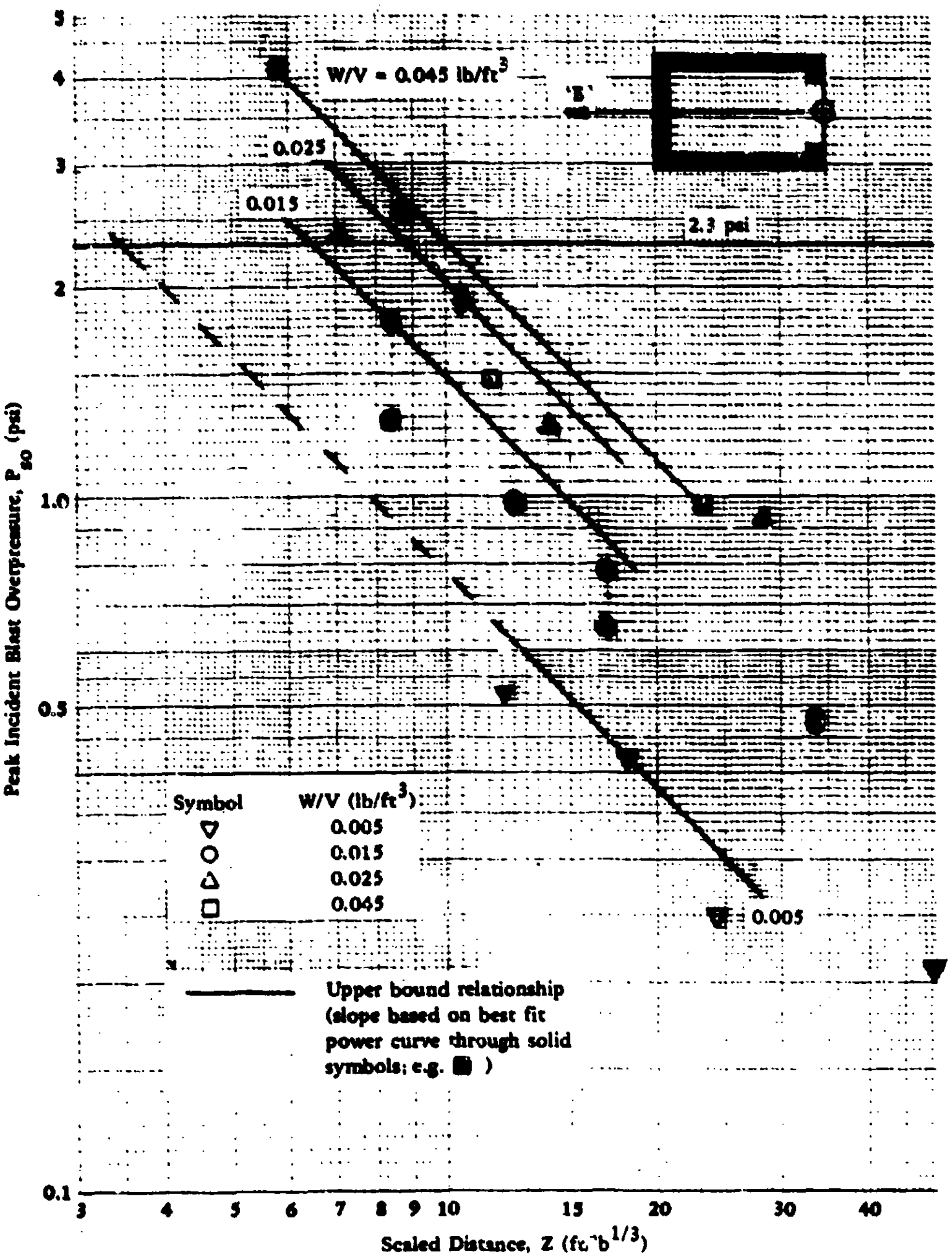

Figure 20. P_{so} vs. W/V to the back ('B' direction) of the MTC.

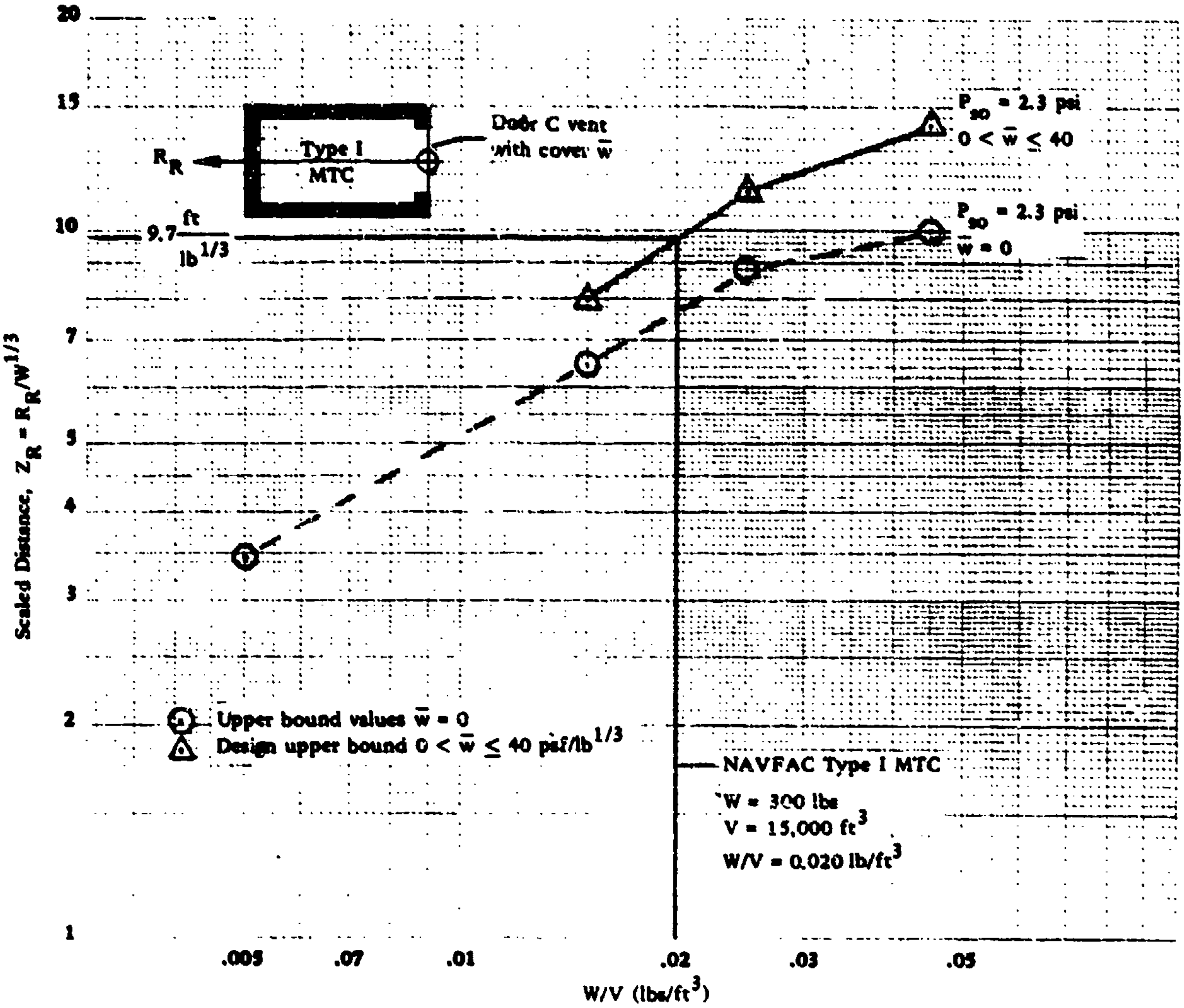

Figure 21. Z_R vs. W/V for P_{so} = 2.3 psi to back of MTC.

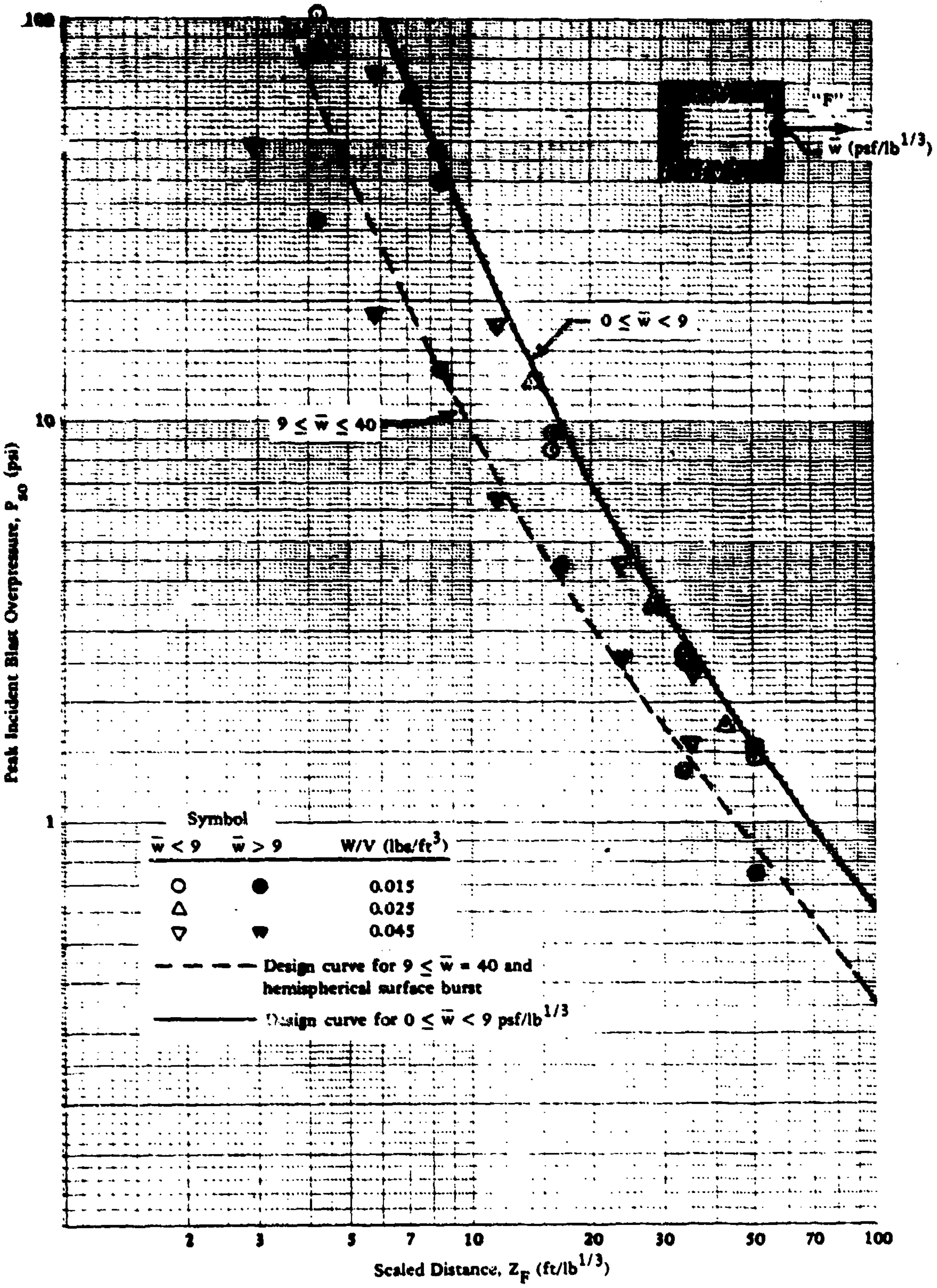

Figure 22. P_{so} design curves, 'F' direction.

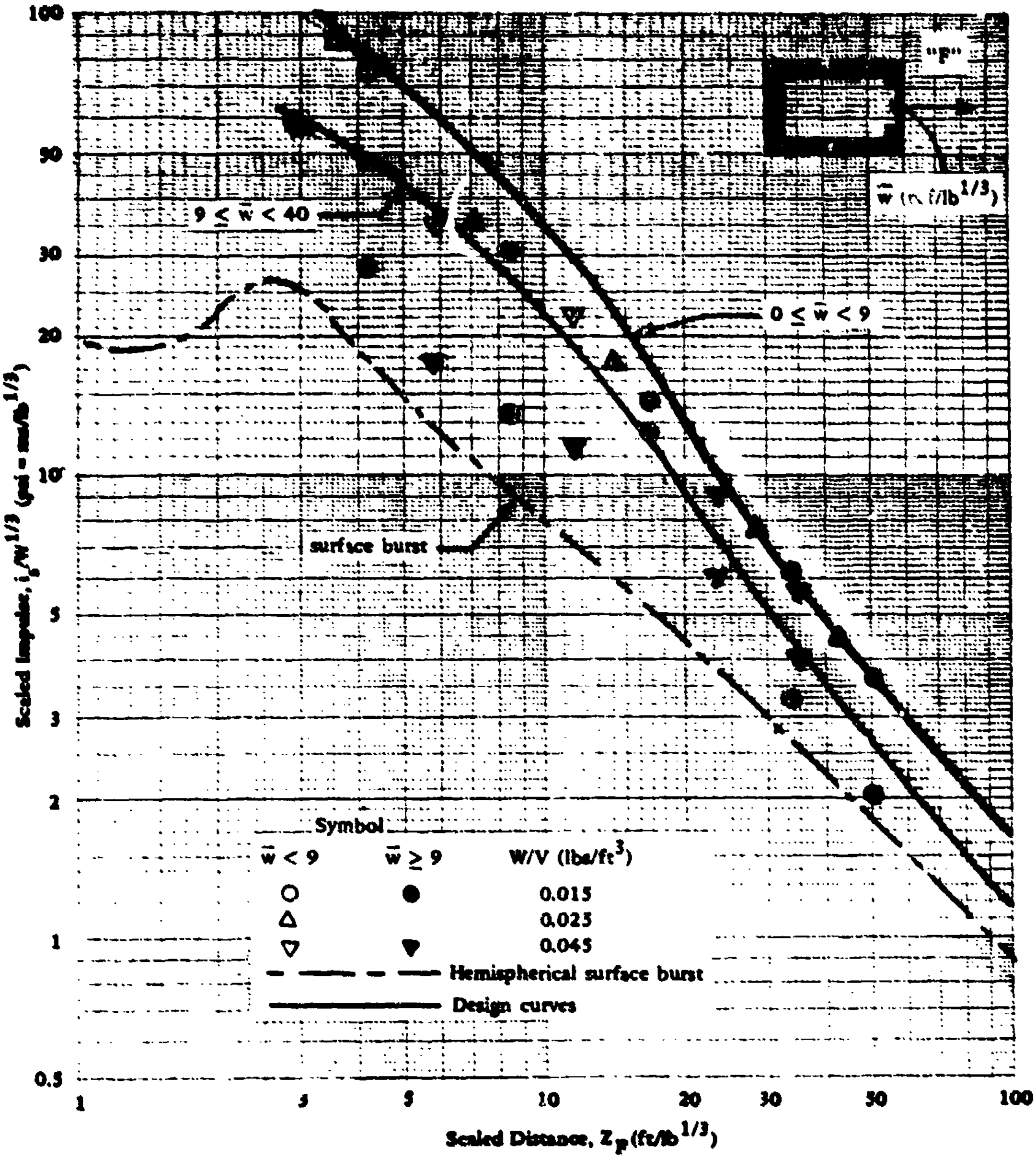

Figure 23. $i_s/W^{1/3}$ design curves, 'F' direction.

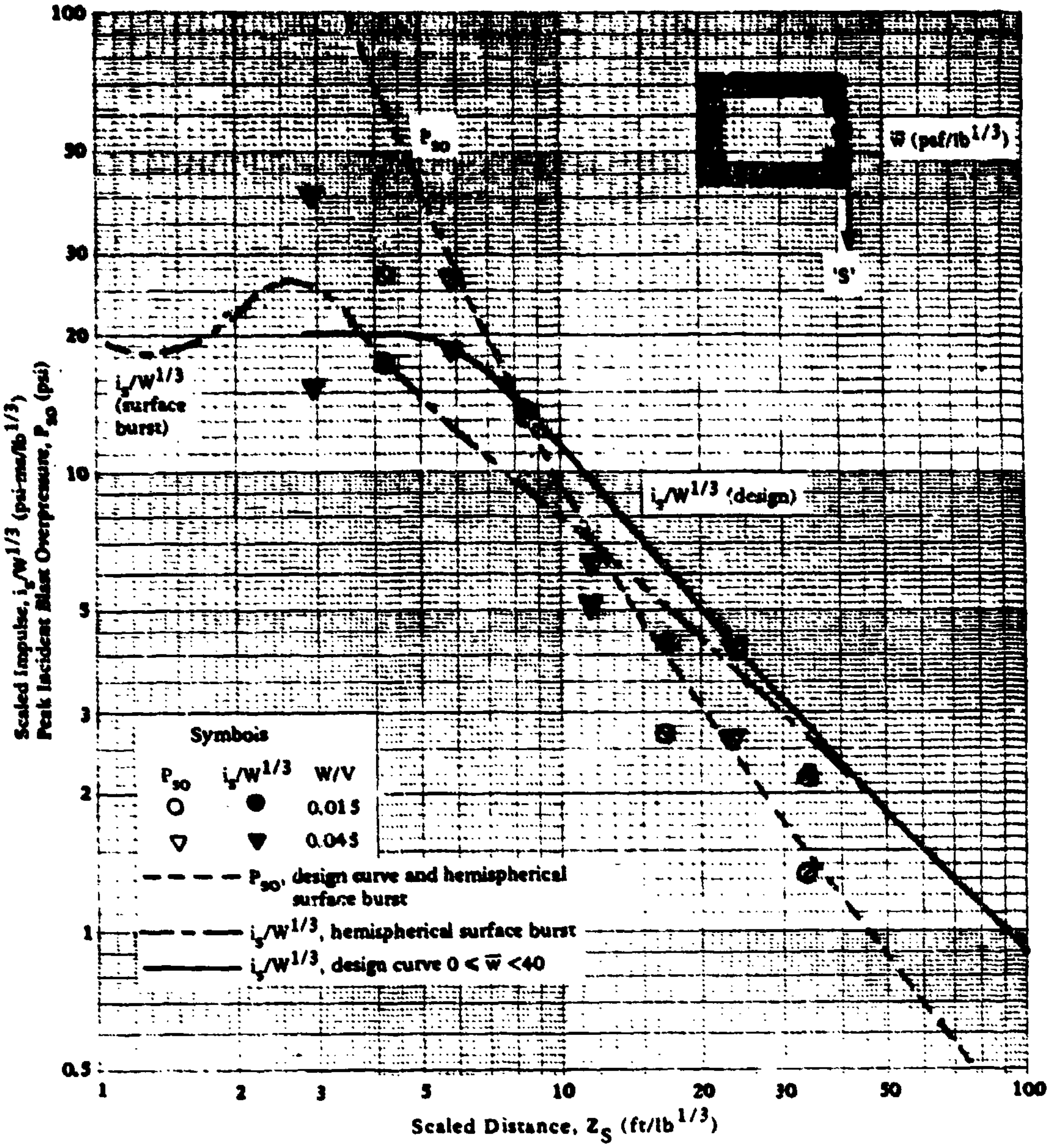

Figure 24. P_{so} and $i_s/W^{1/3}$ design curves, 'S' direction.

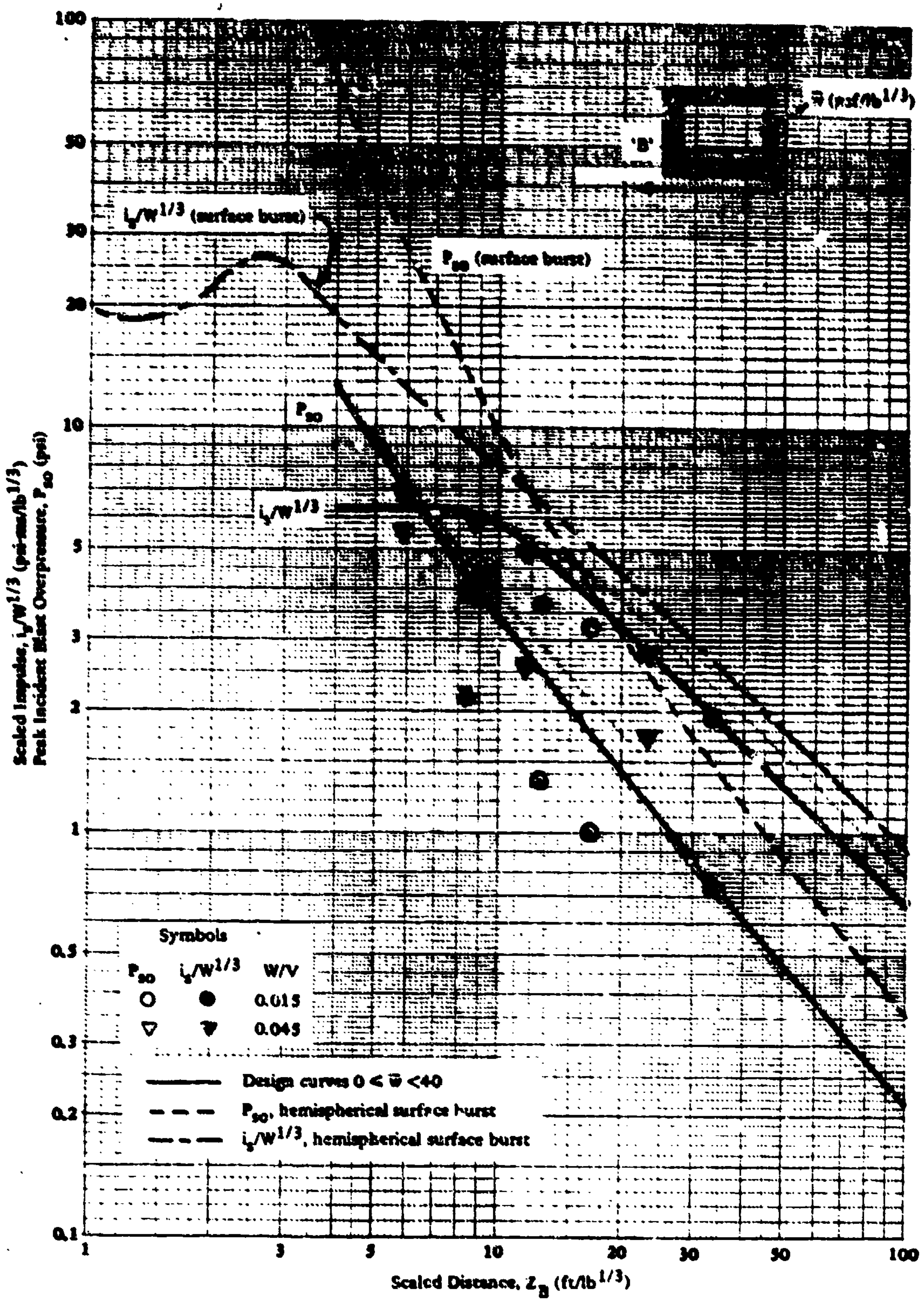

Figure 25. P_{so} and $i_s/W^{1/3}$ design curves, 'B' direction.

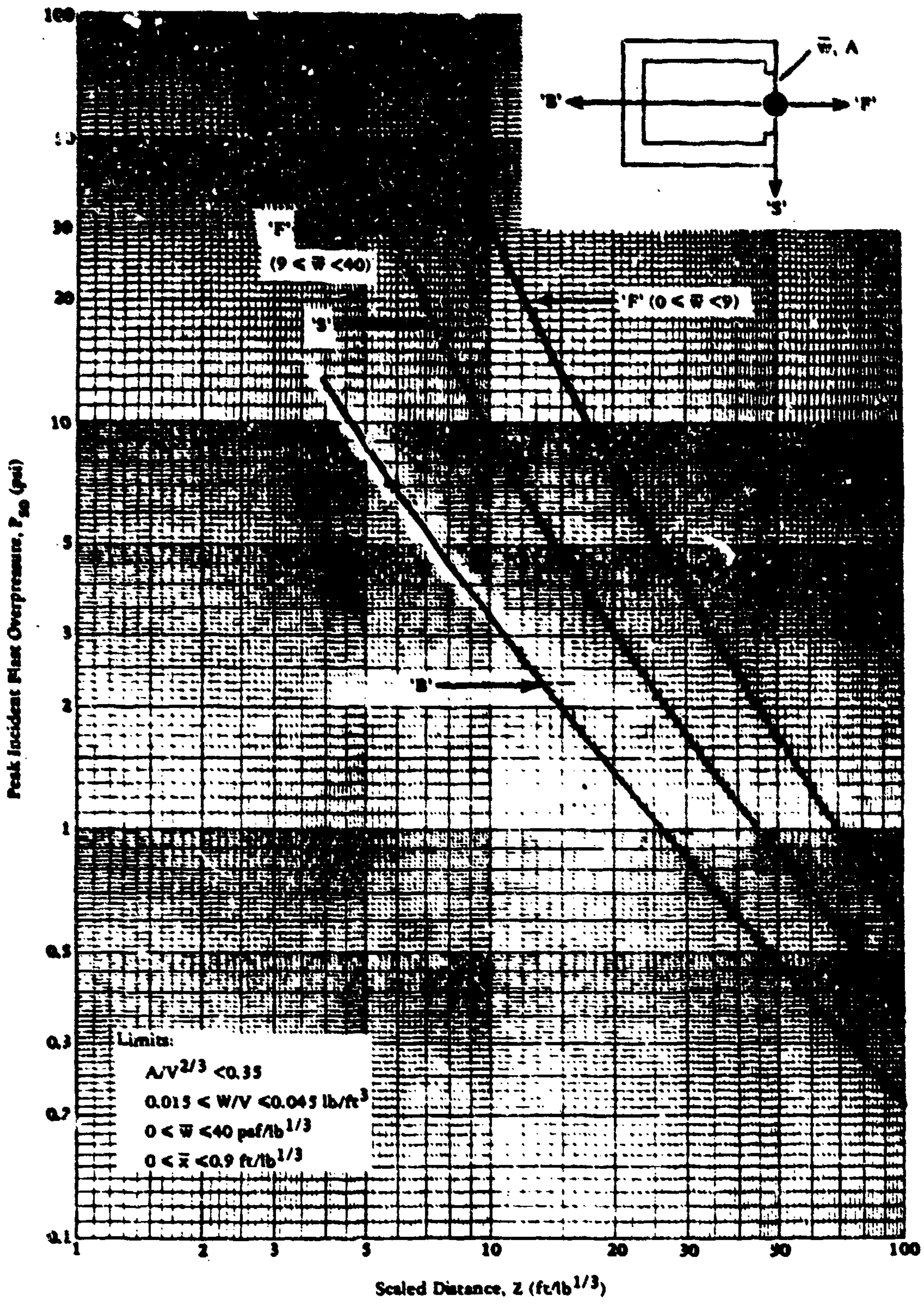

Figure 26. Peak incident design pressure outside NAVFAC MTC.

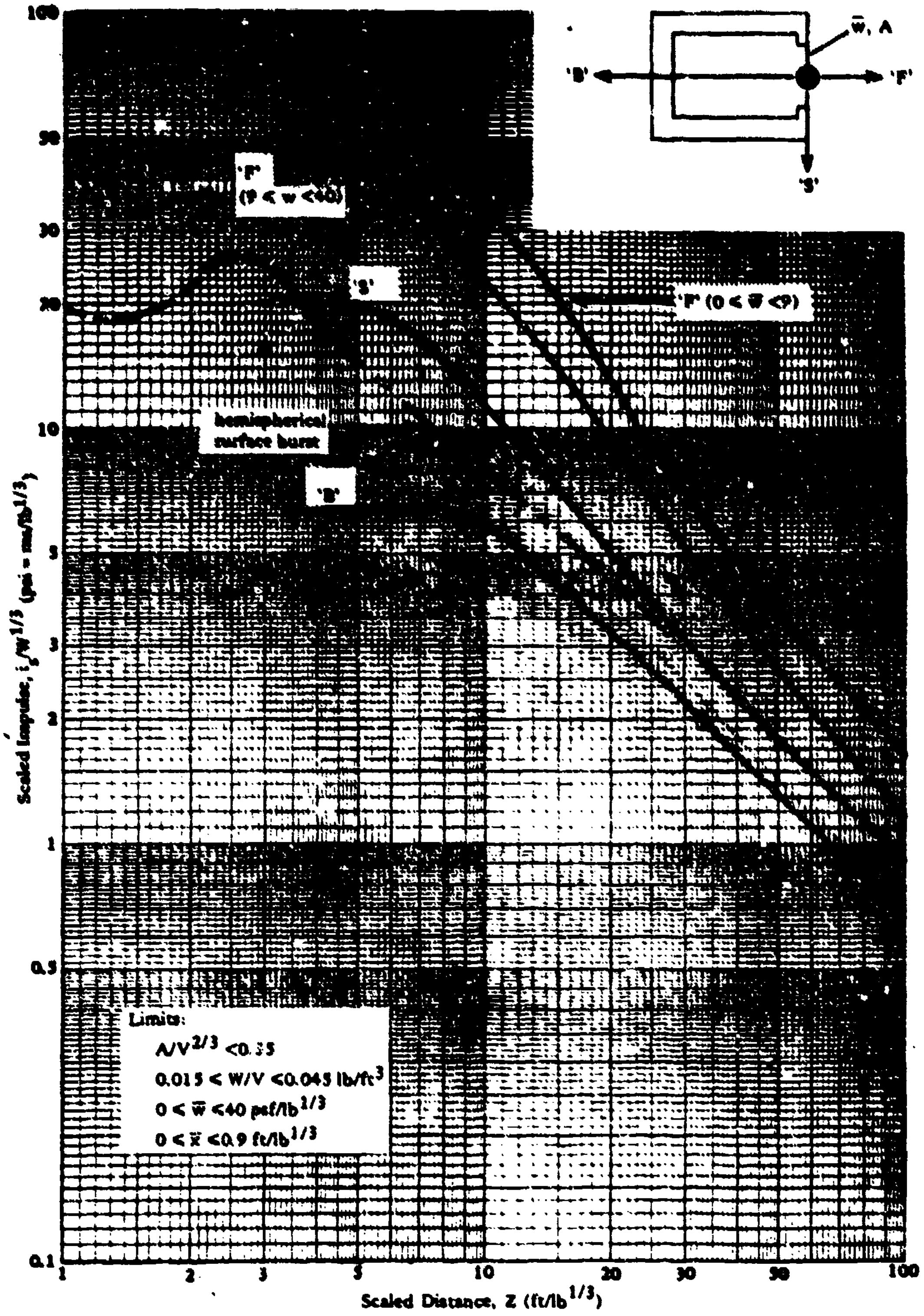

Figure 27. Scaled incident design impulse outside NAVFAC MTC.

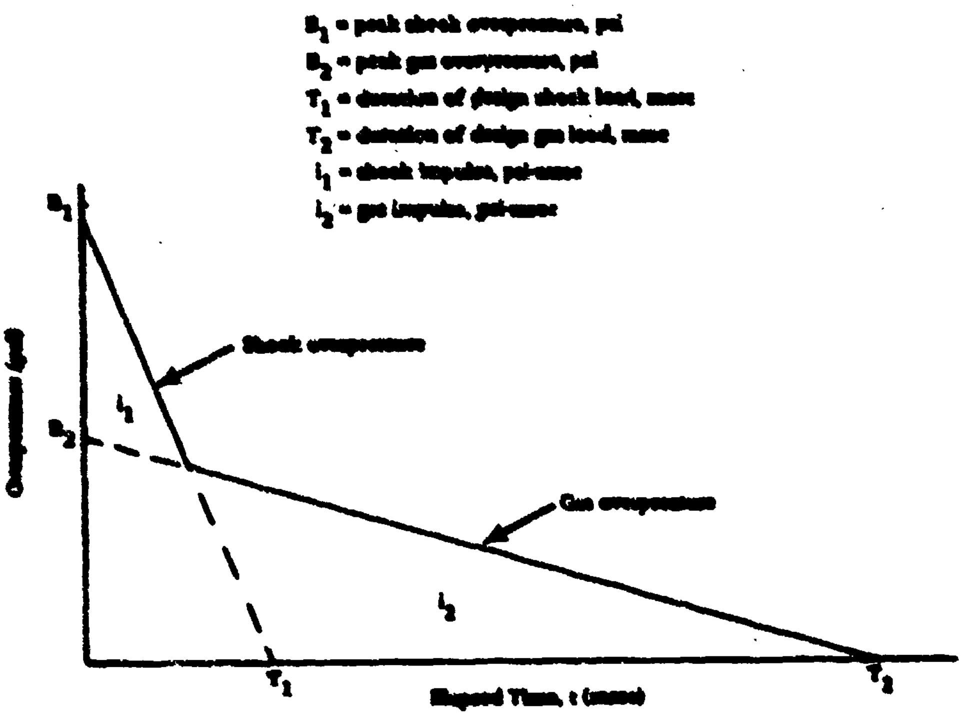
B1 = peak shock overpressure, psi
B2 = peak gas overpressure, psi
T1 = duration of design shock load, msec
T2 = duration of design gas load, msec
i1 = shock impulse, psi-msec
i2 = gas impulse, psi-msec
B1
B2
Shock overpressure
Gas overpressure
i1
i2
Overpressure (psi)
T1
T2
Elapsed Time, t (msec)

Figure 28. Combined internal design loading for MTC.

BLAST LOADS BEHIND VERTICAL WALLS

Prepared for the

Twenty-Second DoD Explosives Safety Seminar

Anaheim, California

26-28 August 1986

by

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1.0 PURPOSE

This paper presents preliminary design criteria for vertical cantilever blast deflector walls intended to reduce the blast environment from explosions detonated immediately behind the walls. The design criteria relates the peak blast overpressure, total blast impulse, and effective duration of the overpressure in a format that facilitates the design of blast deflector walls and the prediction of the blast environment behind the walls. The preliminary criteria presented in this paper were derived from high explosive tests completed in 1985 (Reference 1 and 2). Additional tests are scheduled for September 1986 (Reference 3), and final design criteria will then be developed.

2.0 PROBLEM

Vehicle bombs are a major terrorist threat to the security and safety of inhabited facilities. One possible plan to reduce the danger of the vehicle bombs is to construct a vertical cantilever wall at a safe distance from the nearest people and property. The wall is designed to stop the vehicle and to prevent breaching of the wall from detonation of the bomb. The wall serves to detonate the vehicle bomb a safe distance away from the inhabited facilities.

The procedure for designing the wall to survive the vehicle impact and bomb explosion is undefined. Some criteria exist, but the reliability of the design process decreases with increasing vehicle strike velocity and bomb size, and decreasing distance between the wall and point of detonation. The barrier could be a solid reinforced concrete wall, a composite wall of sand between two reinforced concrete walls connected by shear diaphragms, or a solid reinforced concrete wall backed by a massive earth berm (retaining wall).

One problem in the design of a vehicle bomb barrier is determining where to site the wall relative to the buildings to be protected. Criteria exist for predicting the damage to buildings, given the blast environment at the building. However, no criteria exist for predicting the blast environment behind a vertical wall. Based on the present technology, the site location must neglect any benefits from the wall on reducing the blast environment. Theoretically, the wall serves as a blast deflector shield which reduces the blast environment behind the wall. The effectiveness of the wall in suppressing the blast environment depends on the wall height, and the explosive size and location as illustrated in Figure 1.

The blast environment behind the wall may be further suppressed by locating a canopy near the top of the wall on the loaded side of the wall, as shown in Figure 2. This concept assumes that the canopy would focus shock waves in a safe direction. The canopy could shatter, and be blown away by the force of the explosion, but it would probably remain in place long enough to mitigate the shock waves spilling over the wall. The effectiveness of the canopy depends on its mass, surface area, and location.

Blast pressures measured in high-explosive tests of cubicles by NCEL (Reference 4) demonstrate that reductions in the blast environment behind walls do occur. However, these tests did not simulate the condition of a bomb located adjacent to a long vertical wall designed to prevent shock waves from clearing around the ends of the wall.

Design criteria for the blast environment (including peak blast overpressure, total blast impulse, and effective duration of the overpressure), behind a wall would allow site planners to account for any benefit from the wall on the safe distance required from a vehicle bomb barrier to an inhabited building. The design blast loads must be related to the critical parameters associated with the characteristics of the wall, bomb, and the point of interest behind the wall, as illustrated by the curves in Figures 1 and 2.

3.0 TESTS

3.1 Objective

The objective of this test program was to obtain blast overpressure data from high-explosive tests, using a small scale wall, to empirically derive criteria for the design blast loading at any point behind a vertical blast deflector wall. The criteria will express the peak blast overpressure, B (psi), blast impulse, i (psi-msec), and effective load duration, T (msec), as functions of the net explosive weight, W (lb TNT equivalent), wall height, H (feet), wall length, L (feet), distance to point of interest behind wall, R (feet), elevation of point of interest behind wall, h (feet), charge-to-wall distance, r (feet), elevation of charge above ground, z (feet), canopy width, L' (feet), canopy elevation above ground H' (feet), and canopy mass, w (lb/ft^2).

The measured blast environment behind the wall will be compared with existing relationships for a surface burst without a wall. The benefits of a vertical wall and a vertical wall plus canopy in reducing the blast environment will be assessed.

3.2 Test Setup

The wall tests were performed at the Terminal Effects Research and Analysis Group (TERA) of the New Mexico Institute of Mining and Technology in Socorro, New Mexico. The test schedule is shown in Table 1.

The test structure was a vertical cantilever wall, 2.25 feet high and 28.67 feet long. The wall was constructed of steel armor plate as shown in Figure 3. This test structure is a one-sixth geometric scale model of a 13.5-foot-high by 172-foot-long cantilever wall.

The canopies used for tests 2, 3, 5, 6, and 7 were six-guage or twelve-guage steel sheet metal. Three canopy designs were used in the testing (width = 1.0 feet and density = 4.38 psf; width = 1.0 feet and density = 8.13 psf; and width = 1.5 feet and density = 8.13 psf). The length of each canopy was ten feet. The canopy mass was chosen to represent the equivalent of a 4-inch-thick reinforced concrete slab. The canopies were attached to the wall by a series of tack welds. The tack welding provided the support for the canopy to keep it perpendicular to the wall, but did not prevent the canopy from being blown off the wall when the explosive charge was detonated. For tests 9 and 10, the canopies were supported by several rebar tack welded perpendicular to the wall; the canopies used in tests 9 and 10 were not attached to the wall by any welds.

The test program involved three charge weights (W_{C4} = 1.0, 8.0, and 15.0 pounds C4 explosive). The explosives used in the tests were spherical composition C4 charges. Each explosive charge was placed in a lightweight cheesecloth pouch and suspended by string from a rebar welded perpendicular to the wall. The distance from the center of the charge to the wall and to the ground was one foot. Conversion of charge weight from composition C4 to TNT was made using an equivalency value of 1.129 (1.129 pounds of TNT is equal to 1.0 pounds of C4, Reference 5). According to modeling laws, detonating a 1.0-pound test charge adjacent to the scale model wall is equivalent to detonating a 244-pound charge adjacent to the prototype wall, and detonating a 15.0-pound test charge (maximum test charge) adjacent to the scale model wall is equivalent to detonating a 3,660-pound bomb adjacent to the prototype wall.

3.3 Testing Procedure

Pressure transducers were located along two horizontal gage lines emanating from the charge as shown in Figure 4. One gage line was set up normal to the wall, and the other was 45 degrees to the wall. Each gage line had transducers located at both the ground surface (h = 0), and at the elevation of the wall (h = H = 2.25 feet). The elevated gages farthest from the wall were 4.5 feet above the ground surface. The transducers normal to the wall were located at R = 2.25, 4.5, 6.75, 9.0, 13.5, and 18.0 feet from the wall. This corresponds to 1H, 2H, 3H, 4H, 6H, and 8H, with the distance from the transducers to the wall given in multiples of the wall height. The gages at 45 degrees to the wall were located at R = 4.5, 9.0, and 18.0 feet from the wall. This corresponds to 2H, 4H, and 8H, with the distance from the transducers to the wall given in multiples of the wall height. This arrangement required eighteen transducers in each test. Based on the one-sixth scale model, the measurement points correspond to full-scale $13.5 \leq R \leq 108$ feet and $0 \leq h \leq 13.5$ feet (h = 27 feet for the two elevated gages farthest from the wall).

Gage mounts for the elevated gages were stainless steel disk baffles supported by steel gage stands oriented in the direction of the charge. The surface gages were installed flush with the ground.

Analog pressure data was electronically recorded on magnetic tape using two tape recorders.

3.4 Test Results

The analog data obtained from each test was digitized, and computer plots of the pressure-time history at each pressure transducer were prepared. The plots showed the peak blast overpressure and the total impulse measured at each gage. The peak pressure, total impulse, and gage locations for each test are summarized in Tables 2 through 11.

In order to compare the test results with the blast environment produced from an explosion without a wall, values for the peak pressure and total impulse were required for the detonation of 1.0, 8.0, and 15.0 pound charges with no blast deflector wall. These values were obtained using the hemispherical surface burst graphs in the revised NAVFAC P-397 Volume II (Reference 6). The calculated values of the peak pressure and total impulse resulting from the detonation of a charge without a wall are given in Table 12.

The barricade was not damaged in any of the ten tests. The canopies were all completely blown away from the wall.

Peak pressure and scaled impulse were plotted against scaled ground distance for each charge weight, showing results for each test with and without canopies, and the calculated values for surface pressure with no wall. These plots are given in Figures 5 through 10. Separate plots were made for the results from the elevated gages and the surface gages, and for the 45 degree gage line and the 90 degree gage line.

In general, there was a reduction in peak pressure and impulse behind the wall when the test results are compared to the calculated values for the blast environment produced from an explosion without a wall.

3.5 Additional Testing

From the results of the tests in October 1985, it was determined that additional testing would be required before blast load criteria could be developed. Values for the peak pressure and total impulse resulting from the detonation of a charge without a wall were calculated using the hemispherical surface burst graphs in the revised NAVFAC P-397. Additional tests are planned to provide data to compare with these values from P-397. Also, blast overpressure data from tests using the small-scale wall are planned for validation of previous results. The test schedule for these tests is given in Table 13.

4.0 PRELIMINARY DESIGN CRITERIA

Presented in Figures 11 through 15 are preliminary design criteria for the blast environment behind vehicle bomb barriers. The criteria are considered to be preliminary and will require further test validation.

Use of the criteria requires interpolation between values corresponding to the curves in Figures 11 through 15. Linear interpolation on a log-log scale is recommended for obtaining an intermediate value of any parameter, using either mathematical relationships or log-log graph paper.

In Figure 11, the blast overpressure, B, and scaled impulse, $i/W^{1/3}$ are plotted as a function of the scaled distance, $R/W^{1/3}$, for several values of the scaled wall height, $H/W^{1/3}$. Each curve is for the results from the surface gages, for tests with no canopy.

In Figure 12, the blast overpressure, B, and scaled impulse, $i/W^{1/3}$ are plotted as a function of the scaled distance, $R/W^{1/3}$, for several values of the scaled canopy mass, $w/W^{1/3}$. Each curve is for the results from the surface gages, for tests with the scaled wall height, $H/W^{1/3}$, equal to 0.88 $ft/lb^{1/3}$.

In Figure 13, the blast overpressure, B, and scaled impulse, $i/W^{1/3}$ are plotted as a function of the scaled distance, $R/W^{1/3}$, for several values of the scaled canopy mass, $w/W^{1/3}$. Each curve is for the results from the surface gages, for tests with the scaled wall height, $H/W^{1/3}$, equal to 1.08 $ft/lb^{1/3}$.

In Figure 14, the blast overpressure, B, and scaled impulse, $i/W^{1/3}$ are plotted as a function of the scaled distance, $R/W^{1/3}$, for several values of the scaled canopy mass, $w/W^{1/3}$. Each curve is for the results from the surface gages, for tests with the scaled wall height, $H/W^{1/3}$, equal to 2.16 $ft/lb^{1/3}$.

In Figure 15, the blast overpressure, B, and scaled impulse, $i/W^{1/3}$ are plotted as a function of the scaled distance, $R/W^{1/3}$, for several values of the scaled wall height, $H/W^{1/3}$. Each curve is for the results from the elevated gages, for tests with no canopy.

5.0 FUTURE WORK

Additional explosive tests are planned for September 1986. These tests are considered important to validate the results of the previous test series, and to provide data for blast overpressure with no blast deflector wall. The test results will be combined with previous results to empirically derive design criteria for the blast environment behind a vehicle bomb barrier.

6.0 REFERENCES

1. Naval Civil Engineering Laboratory. Technical Memorandum TM 51-85-14: Test plan for development of criteria for design blast loads behind a blast deflector wall, by M. Beyer and W. Keenan. Port Hueneme, Calif., Oct 1985.

2. Naval Civil Engineering Laboratory. Technical Memorandum TM 51-86-08: Test Data Report: Development of criteria for design blast loads behind a blast deflector wall, by M. Beyer, Port Hueneme, Calif., Jan 1986.

3. Naval Civil Engineering Laboratory. Technical Memorandum TM 51-86-11: Test plan for additional testing for development of criteria for design blast loads behind a blast deflector wall, by M. Beyer, Port Hueneme, Calif., Jun 1986.

4. Civil Engineering Laboratory. Technical Report R-828: Blast environment from fully and partially vented explosions in cubicles, by W. A. Keenan and J. E. Tancreto. Por Hueneme, Calif., Nov 1975.

5. US Department of Energy. DOE/TIC-11268: A manual for the prediction of blast and fragment loadings on structures, by W. Baker, J. Kulesz, P. Westine, P. Cox, and J. Wilbeck. Nov 1980, Appendix A, Table 6.

6. Naval Facilities Engineering Command. NAVFAC P-397. Army TM 5-1300 and Air Force AFM 88-22, Special Publication ARLCD-SP-84001: Structures to resist the effects of accidental explosions. Washington, D. C., Jun 1969, Volume 2.

7.0 LIST OF SYMBOLS

B = Peak Blast Overpressure, (psi)

i = Blast Impulse, (psi-msec)

T = Effective Load Duration, (msec)

W = Net Explosive Weight, (lbs TNT equivalent)

W_{C4} = Net Explosive Weight, (lbs Composition C4 explosive)

H = Wall Height, (feet)

L = Wall Length, (feet)

R = Distance to Point of Interest Behind Wall, (feet)

h = Elevation of Point of Interest Behind Wall, (feet)

r = Charge-to-wall Distance, (feet)

z = Elevation of Charge Above Ground, (feet)

L' = Canopy Width, (feet)

H' = Canopy Elevation Above Ground, (feet)

w = Canopy Mass, (lb/ft^2)

Z = Scaled Distance to Point of Interest Behind Wall, $R/W^{1/3}$, ($feet/lb^{1/3}$)

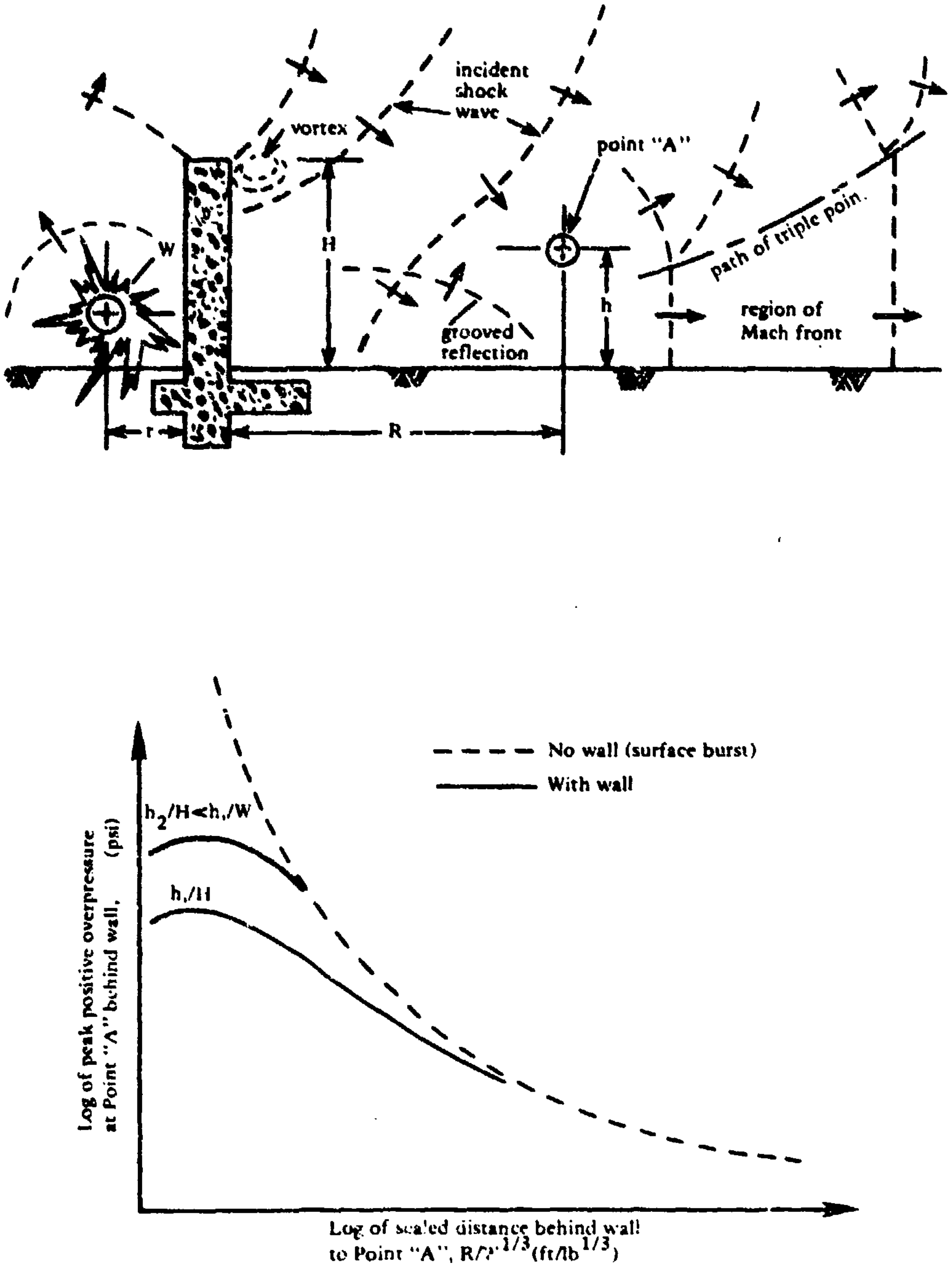

Figure 1. Blast deflector wall and blast environment behind wall.

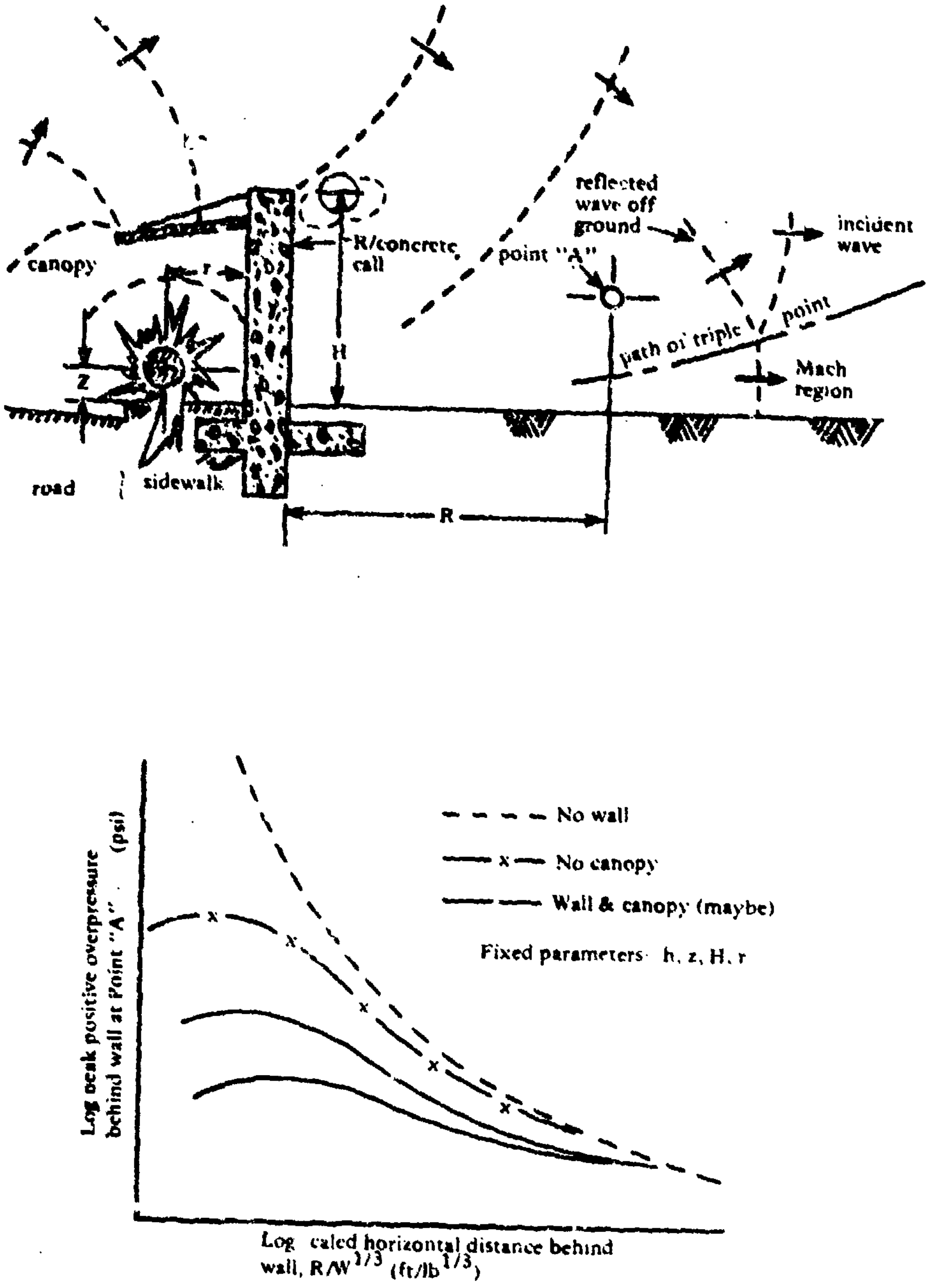
reflected
wave off
ground
incident
wave
canopy
R/concrete
wall
point "A"
H
z
r
path of triple point
Mach
region
road
sidewalk
R
No wall
No canopy
Wall & canopy (maybe)
Fixed parameters: h, z, H, r
Log peak positive overpressure behind wall at Point "A" (psi)
Log scaled horizontal distance behind wall, $R/W^{1/3}$ (ft/lb$^{1/3}$)

Figure 2. Canopy wall and blast environment behind wall.

TABLE 1. TEST SCHEDULE (Completed in 1985)

TEST NO.	W_{C4} (lbs)	$H/W^{1/3}$	w (psf)	$w/W^{1/3}$	L' (ft)	r (ft)	z (ft)
1	1.0	2.16	0	-	1.0	1.0	1.0
2	1.0	2.16	4.38	4.21	1.0	1.0	1.0
3	1.0	2.16	8.13	7.81	1.0	1.0	1.0
4	8.0	1.08	0	-	1.0	1.0	1.0
5	8.0	1.08	4.38	2.10	1.0	1.0	1.0
6	8.0	1.08	8.13	3.90	1.0	1.0	1.0
7	8.0	1.08	8.13	3.90	1.5	1.0	1.0
8	15.0	0.88	0	-	1.0	1.0	1.0
9	15.0	0.88	4.38	1.71	1.0	1.0	1.0
10	15.0	0.88	8.13	3.17	1.0	1.0	1.0

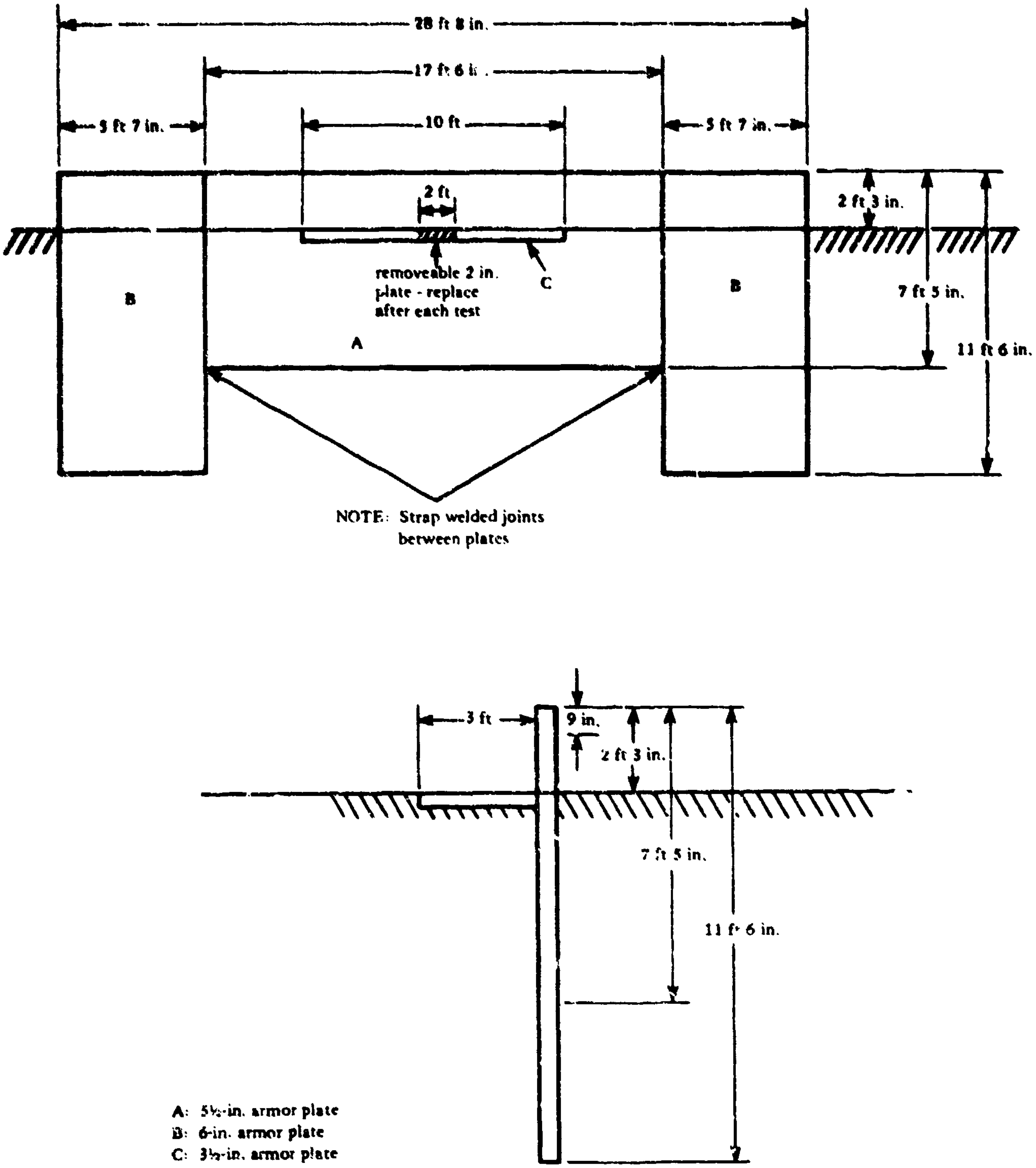

Figure 3. Test wall.

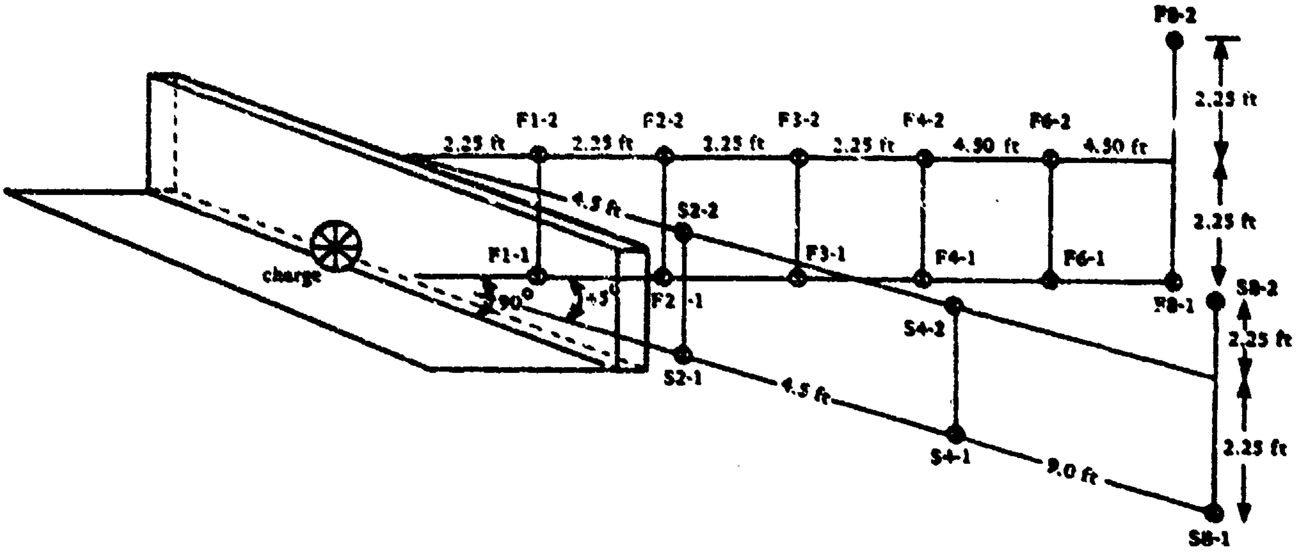

Figure 4. Location of gage lines and pressure transducers.

TABLE 2. TEST 1 RESULTS
Charge Weight = 1.02 lbs
No Canopy

Gage No.	Range R (ft)	Elevation h (ft)	Peak Side-on Overpressure (psi)	Total impulse (psi-msec)
F1-1	2.25	0	15.72	13.0
F1-2	2.25	2.25	16.08	9.0
F2-1	4.50	0	8.32	9.0
F2-2	4.50	2.25	6.28	8.0
F3-1	6.75	0	7.08	8.0
F3-2	6.75	2.25	3.23	6.0
F4-1	9.00	0	6.42	6.0
F4-2	9.00	2.25	3.80	6.0
F6-1	13.50	0	3.52	6.0
F6-2	13.50	2.25	1.87	5.0
F8-1	18.00	0	3.60	5.0
F8-2	18.00	4.50	2.31	4.0
S2-1	4.50	0	13.29	9.0
S2-2	4.50	2.25	9.46	7.0
S4-1	9.00	0	7.63	6.0
S4-2	9.00	2.25	3.06	5.0
S8-1	18.00	0	2.87	4.0
S8-2	18.00	2.25	1.53	4.0

TABLE 3. TEST 2 RESULTS
Charge Weight = 1.02 lbs Canopy Weight = 45.5 lbs
Canopy Size = 12 1/8" x 10' 3/4" x 0.108"

Gage No.	Range R (ft)	Elevation h (ft)	Peak Side-on Overpressure (psi)	Total impulse (psi-msec)
F1-1	2.25	0	6.44	10.0
F1-2	2.25	2.25	6.77	7.0
F2-1	4.50	0	3.89	7.0
F2-2	4.50	2.25	2.87	5.0
F3-1	6.75	0	3.66	6.0
F3-2	6.75	2.25	2.55	5.0
F4-1	9.00	0	3.66	5.0
F4-2	9.00	2.25	2.49	5.0
F6-1	13.50	0	2.56	5.0
F6-2	13.50	2.25	1.72	5.0
F8-1	18.00	0	2.52	4.0
F8-2	18.00	4.50	2.39	4.0
S2-1	4.50	0	4.95	7.0
S2-2	4.50	2.25	4.28	6.0
S4-1	9.00	0	5.68	6.0
S4-2	9.00	2.25	2.51	5.0
S8-1	18.00	0	2.96	4.0
S8-2	18.00	2.25	1.34	3.0

TABLE 4. <u>TEST 3 RESULTS</u>

Charge Weight = 1.02 lbs　Canopy Weight = 78.5 lbs

Canopy Size = 11 7/8" x 10' 3/4" x 0.196"

Gage No.	Range R (ft)	Elevation h (ft)	Peak Side-on Overpressure (psi)	Total impulse (psi-msec)
F1-1	2.25	0	8.40	11.0
F1-2	2.25	2.25	5.28	9.0
F2-1	4.50	0	3.84	7.0
F2-2	4.50	2.25	3.20	6.0
F3-1	6.75	0	3.35	7.0
F3-2	6.75	2.25	2.81	6.0
F4-1	9.00	0	3.40	6.0
F4-2	9.00	2.25	2.73	5.0
F6-1	13.50	0	3.05	5.0
F6-2	13.50	2.25	1.34	5.0
F8-1	18.00	0	1.36	4.0
F8-2	18.00	4.50	1.42	4.0
S2-1	4.50	0	4.91	7.0
S2-2	4.50	2.25	4.67	7.0
S4-1	9.00	0	5.57	6.0
S4-2	9.00	2.25	2.21	4.0
S8-1	18.00	0	2.98	4.0
S8-2	18.00	2.25	1.26	4.0

TABLE 5. <u>TEST 4 RESULTS</u>

Charge Weight = 8.0 lbs

No Canopy

Gage No.	Range R (ft)	Elevation h (ft)	Peak Side-on Overpressure (psi)	Total impulse (psi-msec)
F1-1	2.25	0	29.84	36.0
F1-2	2.25	2.25	29.57	22.0
F2-1	4.50	0	36.00	29.0
F2-2	4.50	2.25	21.83	23.0
F3-1	6.75	0	26.85	32.0
F3-2	6.75	2.25	13.98	28.0
F4-1	9.00	0	16.31	25.0
F4-2	9.00	2.25	7.05	20.0
F6-1	13.50	0	9.70	20.0
F6-2	13.50	2.25	6.79	20.0
F8-1	18.00	0	7.45	18.0
F8-2	18.00	4.50	5.68	18.0
S2-1	4.50	0	28.39	37.0
S2-2	4.50	2.25	no data	no data
S4-1	9.00	0	24.40	25.0
S4-2	9.00	2.25	24.59	25.0
S8-1	18.00	0	7.80	14.0
S8-2	18.00	2.25	5.57	16.0

TABLE 6. TEST 5 RESULTS

Charge Weight = 8.0 lbs Canopy Weight = 46.5 lbs

Canopy Size = 12" x 10' 1/2" x 0.105"

Gage No.	Range R (ft)	Elevation h (ft)	Peak Side-on Overpressure (psi)	Total Impulse (psi-msec)
F1-1	2.25	0	19.74	30.0
F1-2	2.25	2.25	20.91	25.0
F2-1	4.50	0	22.26	31.0
F2-2	4.50	2.25	11.94	24.0
F3-1	6.75	0	17.32	29.0
F3-2	6.75	2.25	9.71	29.0
F4-1	9.00	0	13.94	21.0
F4-2	9.00	2.25	5.45	14.0
F6-1	13.50	0	9.33	17.0
F6-2	13.50	2.25	5.85	15.0
F8-1	18.00	0	5.97	15.0
F8-2	18.00	4.50	4.86	13.0
S2-1	4.50	0	18.64	27.0
S2-2	4.30	2.25	19.45	25.0
S4-1	9.00	0	18.79	18.0
S4-2	9.00	2.25	27.41	21.0
S8-1	18.00	0	6.92	10.0
S8-2	18.00	2.25	3.90	10.0

TABLE 7. TEST 6 RESULTS

Charge Weight = 8.0 lbs Canopy Weight = 79.5 lbs

Canopy Size = 12" x 10' 3/4" x 0.189"

Gage No.	Range R (ft)	Elevation h (ft)	Peak Side-on Overpressure (psi)	Total Impulse (psi-msec)
F1-1	2.25	0	13.78	16.0
F1-2	2.25	2.25	18.17	21.0
F2-1	4.50	0	15.45	34.0
F2-2	4.50	2.25	8.02	26.0
F3-1	6.75	0	15.67	32.0
F3-2	6.75	2.25	10.57	29.0
F4-1	9.00	0	14.10	22.0
F4-2	9.00	2.25	7.12	15.0
F6-1	13.50	0	8.41	17.0
F6-2	13.50	2.25	5.91	16.0
F8-1	18.00	0	6.52	15.0
F8-2	18.00	4.50	6.75	15.0
S2-1	4.50	0	15.98	29.0
S2-2	4.50	2.25	17.93	27.0
S4-1	9.00	0	16.30	18.0
S4-2	9.00	2.25	23.94	22.0
S8-1	18.00	0	6.56	11.0
S8-2	18.00	2.25	3.90	11.0

TABLE 8. TEST 7 RESULTS

Charge Weight = 8.0 lbs   Canopy Weight = 119.0 lbs

Canopy Size = 18" x 10' 3/4" x 0.189"

Gage No.	Range R (ft)	Elevation h (ft)	Peak Side-on Overpressure (psi)	Total impulse (psi-msec)
F1-1	2.25	0	12.93	26.0
F1-2	2.25	2.25	12.61	25.0
F2-1	4.50	0	10.60	27.0
F2-2	4.50	2.25	6.98	23.0
F3-1	6.75	0	9.64	26.0
F3-2	6.75	2.25	8.13	25.0
F4-1	9.00	0	8.38	19.0
F4-2	9.00	2.25	5.13	13.0
F6-1	13.50	0	7.57	15.0
F6-2	13.50	2.25	4.88	14.0
F8-1	18.00	0	7.56	13.0
F8-2	18.00	4.50	5.07	13.0
S2-1	4.50	0	13.99	25.0
S2-2	4.50	2.25	10.80	24.0
S4-1	9.00	0	13.23	15.0
S4-2	9.00	2.25	16.18	18.0
S8-1	18.00	0	5.62	10.0
S8-2	18.00	2.25	3.86	10.0

TABLE 9. TEST 8

Charge Weight = 15.0 lbs

No Canopy

Gage No.	Range R (ft)	Elevation h (ft)	Peak Side-on Overpressure (psi)	Total impulse (psi-msec)
F1-1	2.25	0	39.34	35.0
F1-2	2.25	2.25	no data	no data
F2-1	4.50	0	39.30	33.0
F2-2	4.50	2.25	20.94	50.0
F3-1	6.75	0	31.11	29.0
F3-2	6.75	2.25	no data	no data
F4-1	9.00	0	23.08	30.0
F4-2	9.00	2.25	8.38	27.0
F6-1	13.50	0	14.20	25.0
F6-2	13.50	2.25	7.80	23.0
F8-1	18.00	0	9.14	22.0
F8-2	18.00	4.50	6.00	21.0
S2-1	4.50	0	41.65	39.0
S2-2	4.50	2.25	no data	no data
S4-1	9.00	0	31.16	32.0
S4-2	9.00	2.25	36.33	37.0
S8-1	18.00	0	11.45	19.0
S8-2	18.00	2.25	7.41	17.0

TABLE 10. TEST 9 RESULTS

Charge Weight = 15.0 lbs Canopy Weight = 45.5 lbs

Canopy Size = 12" x 10' 1/4" x 0.105"

Gage No.	Range R (ft)	Elevation h (ft)	Peak Side-on Overpressure (psi)	Total impulse (psi-msec)
F1-1	2.25	0	33.14	32.0
F1-2	2.25	2.25	37.15	75.0
F2-1	4.50	0	26.48	18.0
F2-2	4.50	2.25	47.63	88.0
F3-1	6.75	0	23.76	18.0
F3-2	6.75	2.25	no data	no data
F4-1	9.00	0	13.16	25.0
F4-2	9.00	2.25	4.91	19.0
F6-1	13.50	0	7.53	21.0
F6-2	13.50	2.25	5.16	20.0
F8-1	18.00	0	5.89	21.0
F8-2	18.00	4.50	4.87	19.0
S2-1	4.50	0	36.50	36.0
S2-2	4.50	2.25	53.30	80.0
S4-1	9.00	0	26.18	24.0
S4-2	9.00	2.25	32.07	28.0
S8-1	18.00	0	11.63	16.0
S8-2	18.00	2.25	6.23	14.0

TABLE 11. TEST 10

Charge Weight = 15.0 lbs Canopy Weight = 79.5 lbs

Canopy Size = 12" x 10' 3/4" x 0.189"

Gage No.	Range R (ft)	Elevation h (ft)	Peak Side-on Overpressure (psi)	Total impulse (psi-msec)
F1-1	2.25	0	13.71	27.0
F1-2	2.25	2.25	27.74	31.0
F2-1	4.50	0	24.67	40.0
F2-2	4.50	2.25	38.14	52.0
F3-1	6.75	0	22.44	38.0
F3-2	6.75	2.25	no data	no data
F4-1	9.00	0	11.95	26.0
F4-2	9.00	2.25	5.21	19.0
F6-1	13.50	0	8.05	23.0
F6-2	13.50	2.25	5.36	21.0
F8-1	18.00	0	8.00	22.0
F8-2	18.00	4.50	6.86	19.0
S2-1	4.50	0	35.52	37.0
S2-2	4.50	2.25	36.93	29.0
S4-1	9.00	0	22.26	23.0
S4-2	9.00	2.25	34.21	31.0
S8-1	18.00	0	11.06	16.0
S8-2	18.00	2.25	6.26	15.0

TABLE 12. CALCULATED SURFACE PRESSURE (NO WALL) FROM P-397

W = 1.13 lb $H/W^{1/3}$ = 2.16

R (ft)	B (psi)	i (psi-msec)	Z ($ft/lb^{1/3}$)
3.71	33.3	22	3.56
5.96	30.1	13	5.72
8.21	15.1	10	7.88
10.46	9.3	8	10.04
14.96	5.0	6	14.36
19.46	3.3	4	18.68

W = 9.03 lb $H/W^{1/3}$ = 1.08

R (ft)	B (psi)	i (psi-msec)	Z ($ft/lb^{1/3}$)
3.71	388.2	42	1.78
5.96	149.0	53	2.86
8.21	77.0	39	3.94
10.46	41.5	30	5.02
14.96	18.2	22	7.18
19.46	10.7	17	9.34

W = 16.94 lb $H/W^{1/3}$ = 0.88

R (ft)	B (psi)	i (psi-msec)	Z ($ft/lb^{1/3}$)
3.71	562.0	46	1.44
5.96	231.0	60	2.32
8.21	119.0	61	3.19
10.46	71.5	46	4.07
14.96	28.8	32	5.82
19.46	16.4	26	7.57

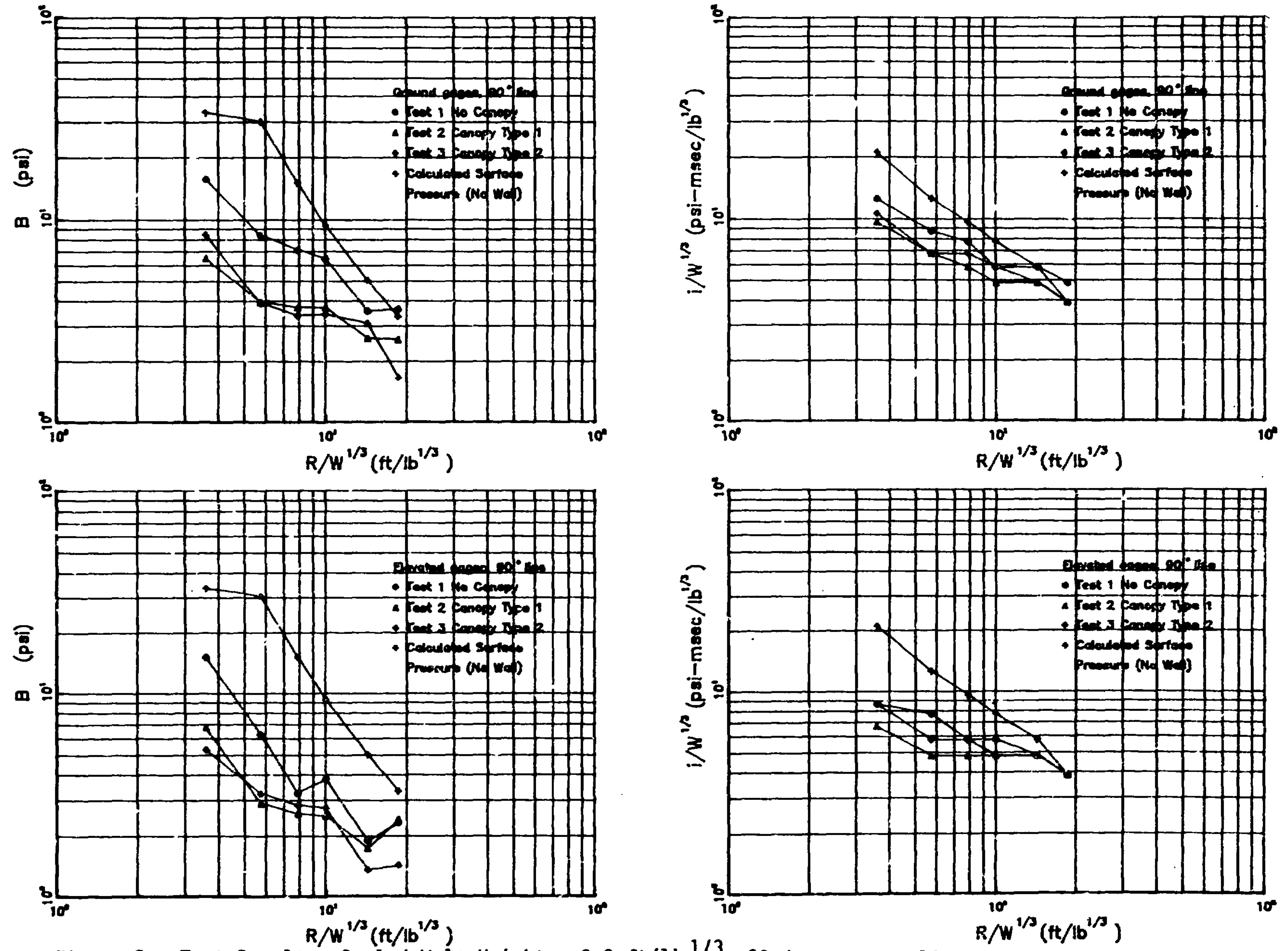

Figure 5. Test Results, Scaled Wall Height = 2.2 ft/lb $^{1/3}$, 90 degree gage line.

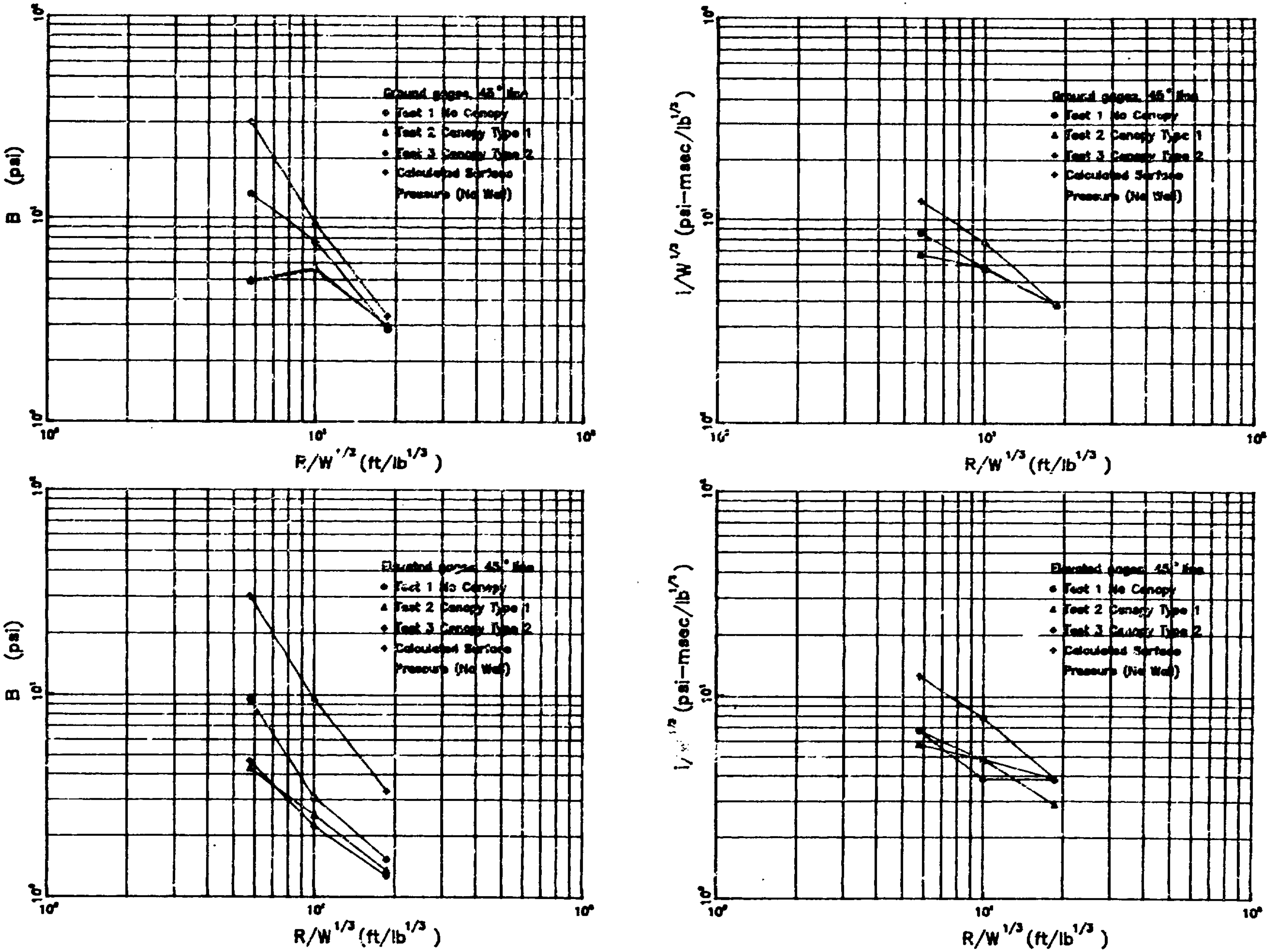

Figure 6. Test Results, Scaled Wall Height = 2.2 ft/lb$^{1/3}$, 45 degree gage line.

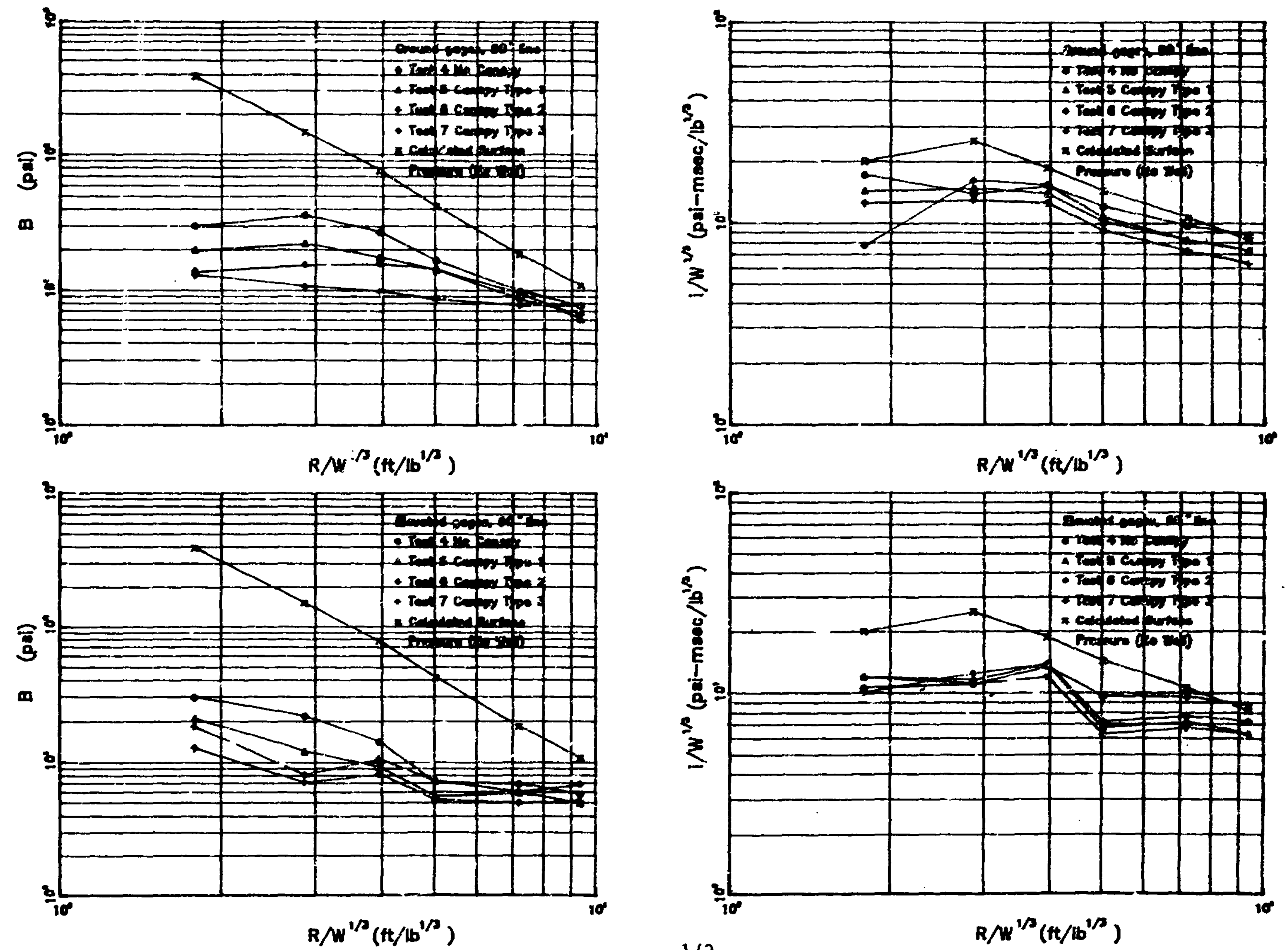

Figure 7. Test Results, Scaled Wall Height = 1.1 ft/$lb^{1/3}$, 90 degree gage line.

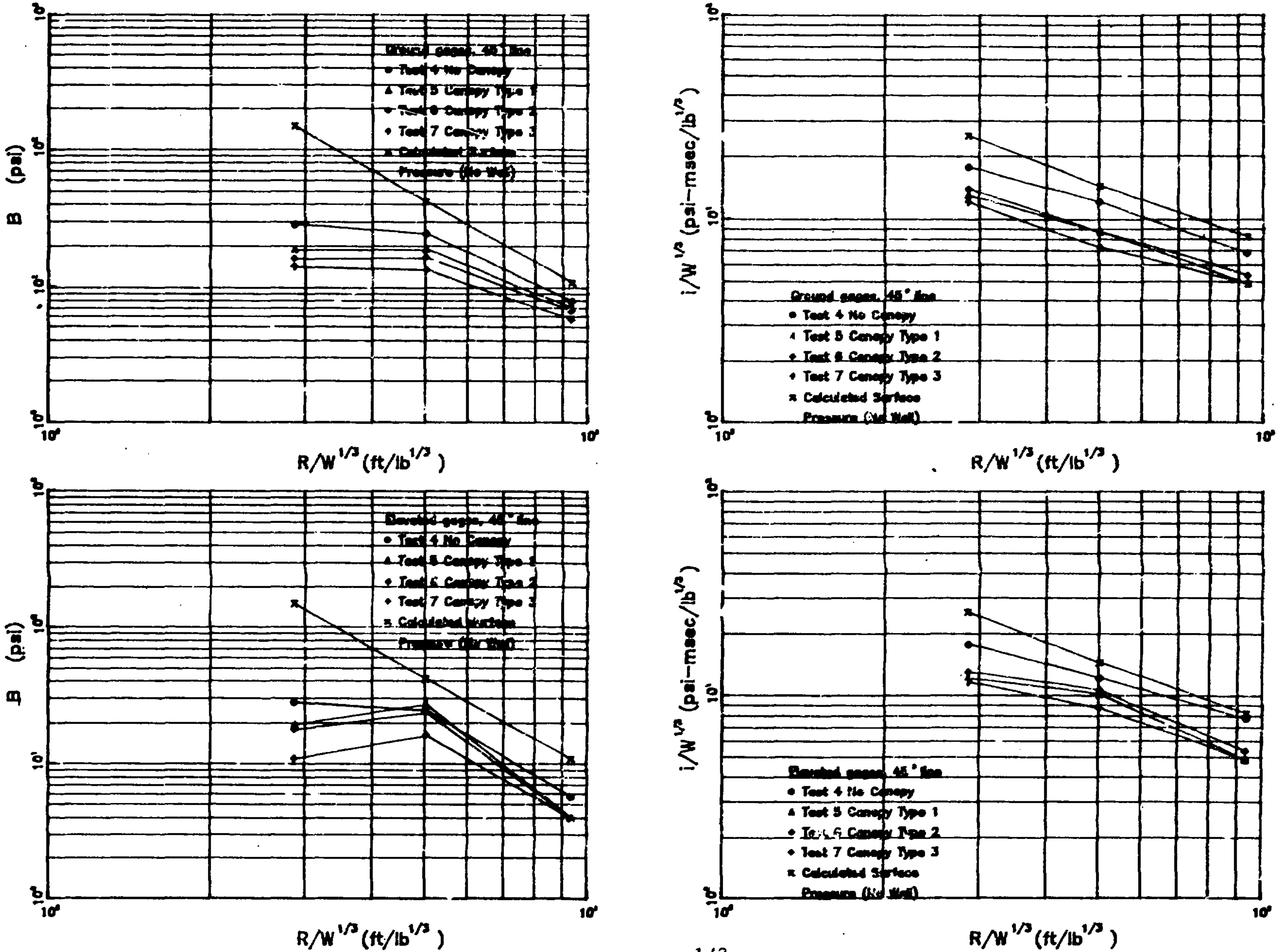

Figure 8. Tests Results, Scaled Wall Height = 1.1 ft/lb$^{1/3}$, 45 degree gage line.

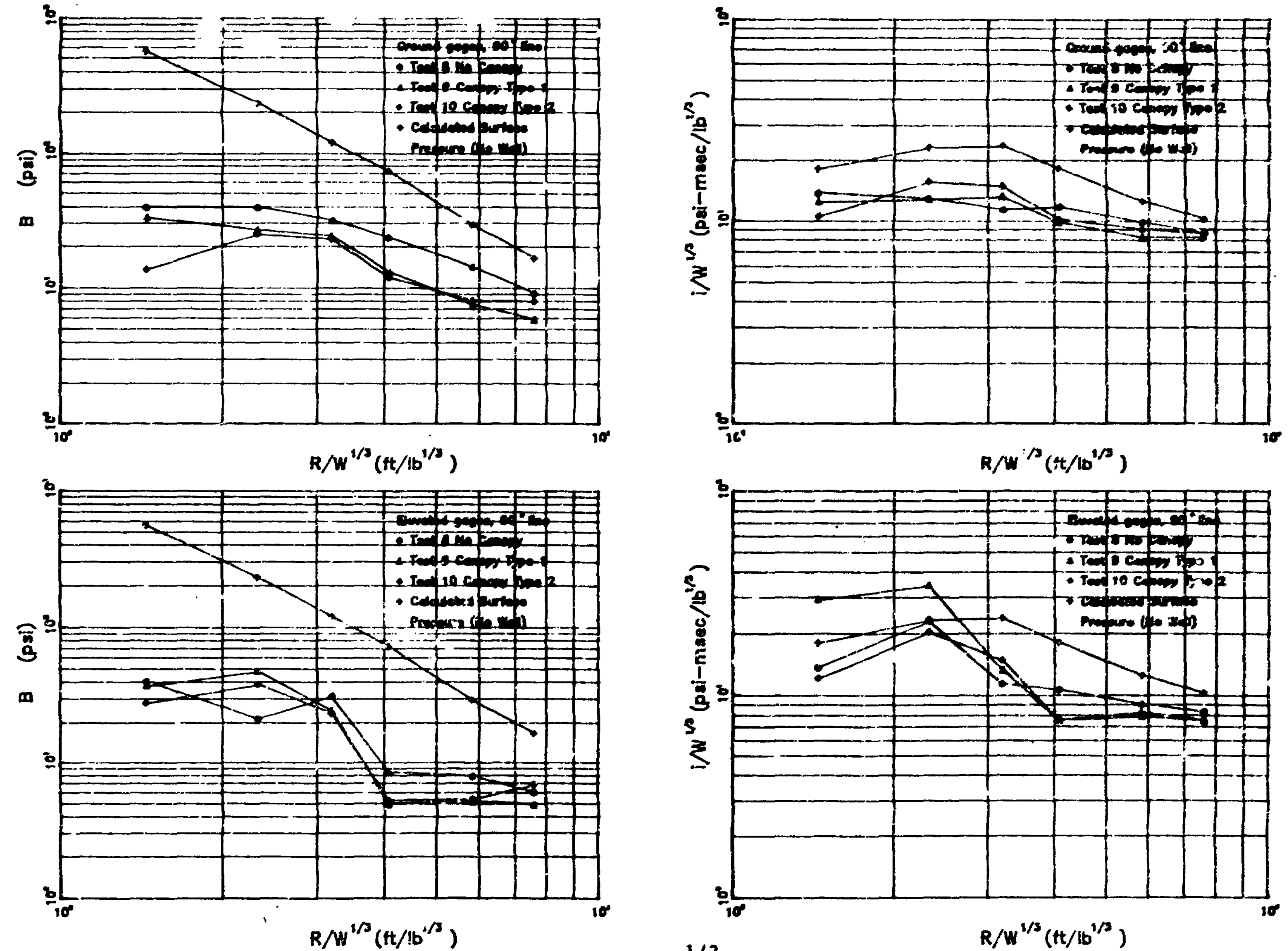

Figure 9. Test Results, Scaled Wall Height = 0.9 ft/lb$^{1/3}$, 90 degree gage line.

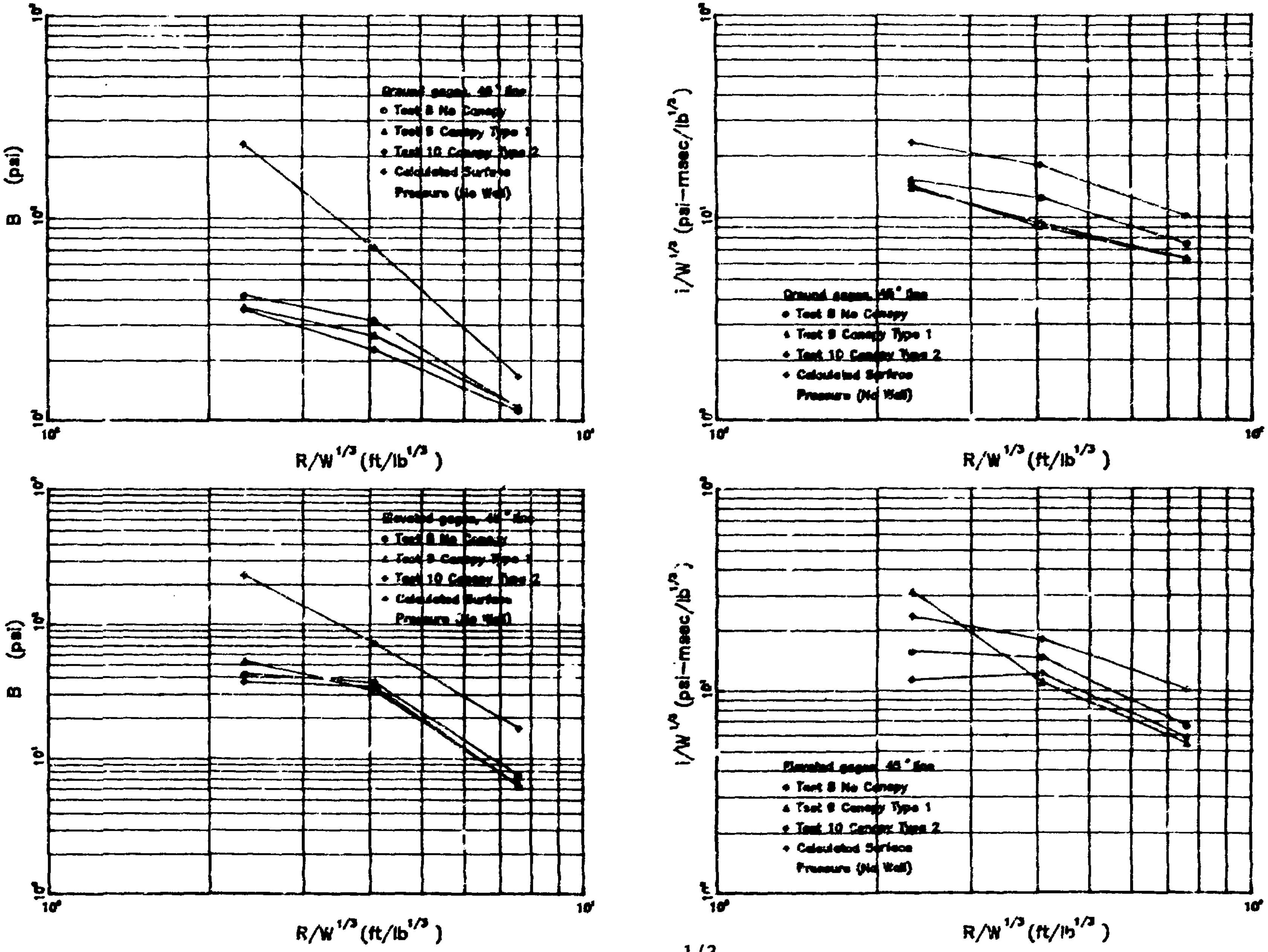

Figure 10. Test Results, Scaled Wall Height = 0.9 ft/lb$^{1/3}$, 45 degree gage line.

TABLE 13. TEST SCHEDULE (SEPTEMBER 1986 PLANNED COMPLETION DATE)

TEST #	W_{C4} (lbs)	Scaled Wall Height (ft)	r (ft)	z (ft)
1	1.0	2.16	1.0	1.0
2	1.0	2.16	2.0	1.0
3	8.0	1.08	1.0	1.0
4	8.0	1.08	2.0	1.0
5	15.0	0.88	1.0	1.0
6	15.0	0.88	2.0	1.0
7	45.6	0.63	2.5	1.23
8	45.6	0.63	2.5	1.23
9	1.0	0.0	*	1.0
10	1.0	0.0	*	1.0
11	8.0	0.0	*	1.0
12	8.0	0.0	*	1.0
13	15.0	0.0	*	1.0
14	15.0	0.0	*	1.0

* For the tests with no wall, the charge will be positioned relative to the pressure transducers.

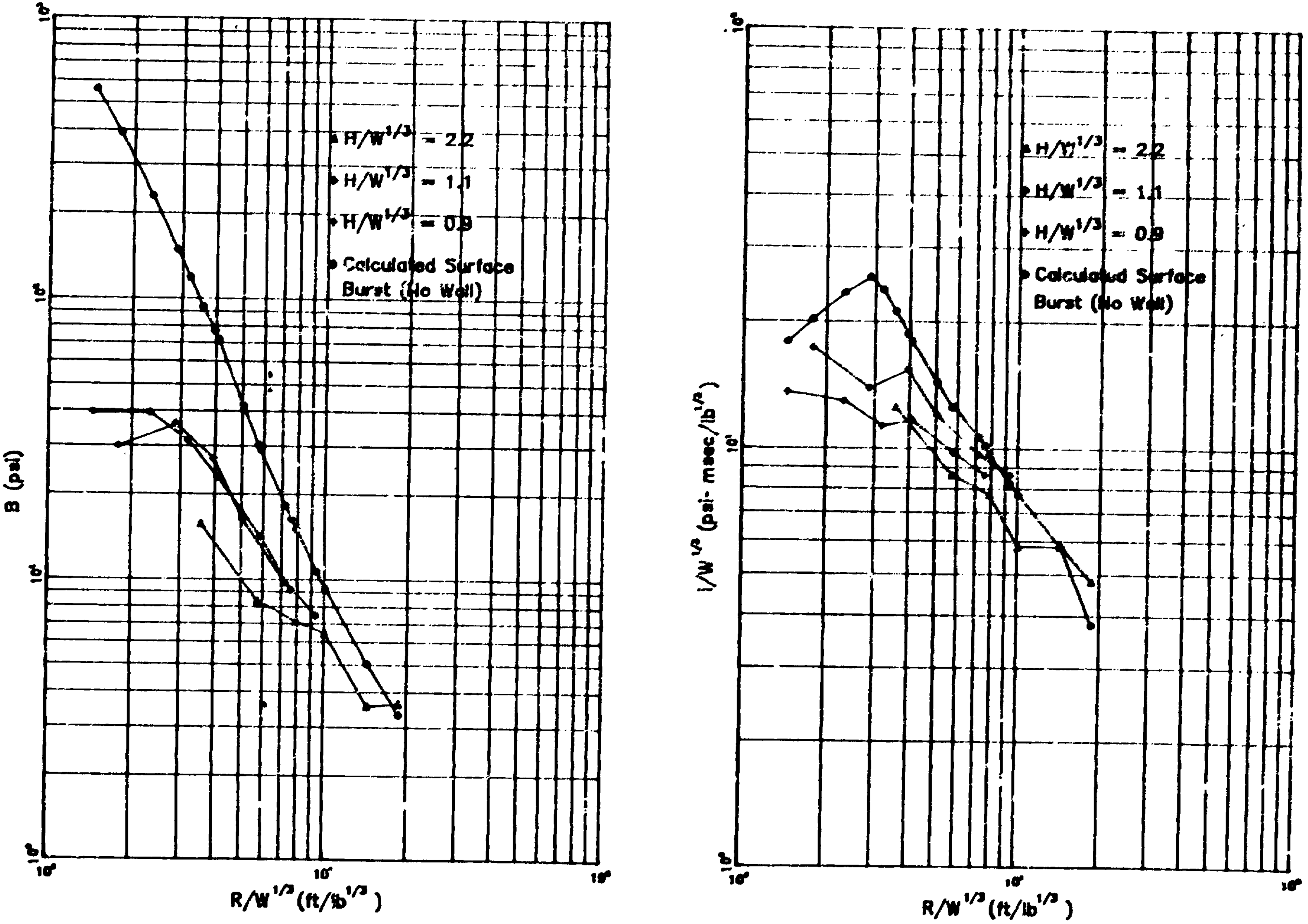

Figure 11. Preliminary design curves. Surface gages, no canopy.

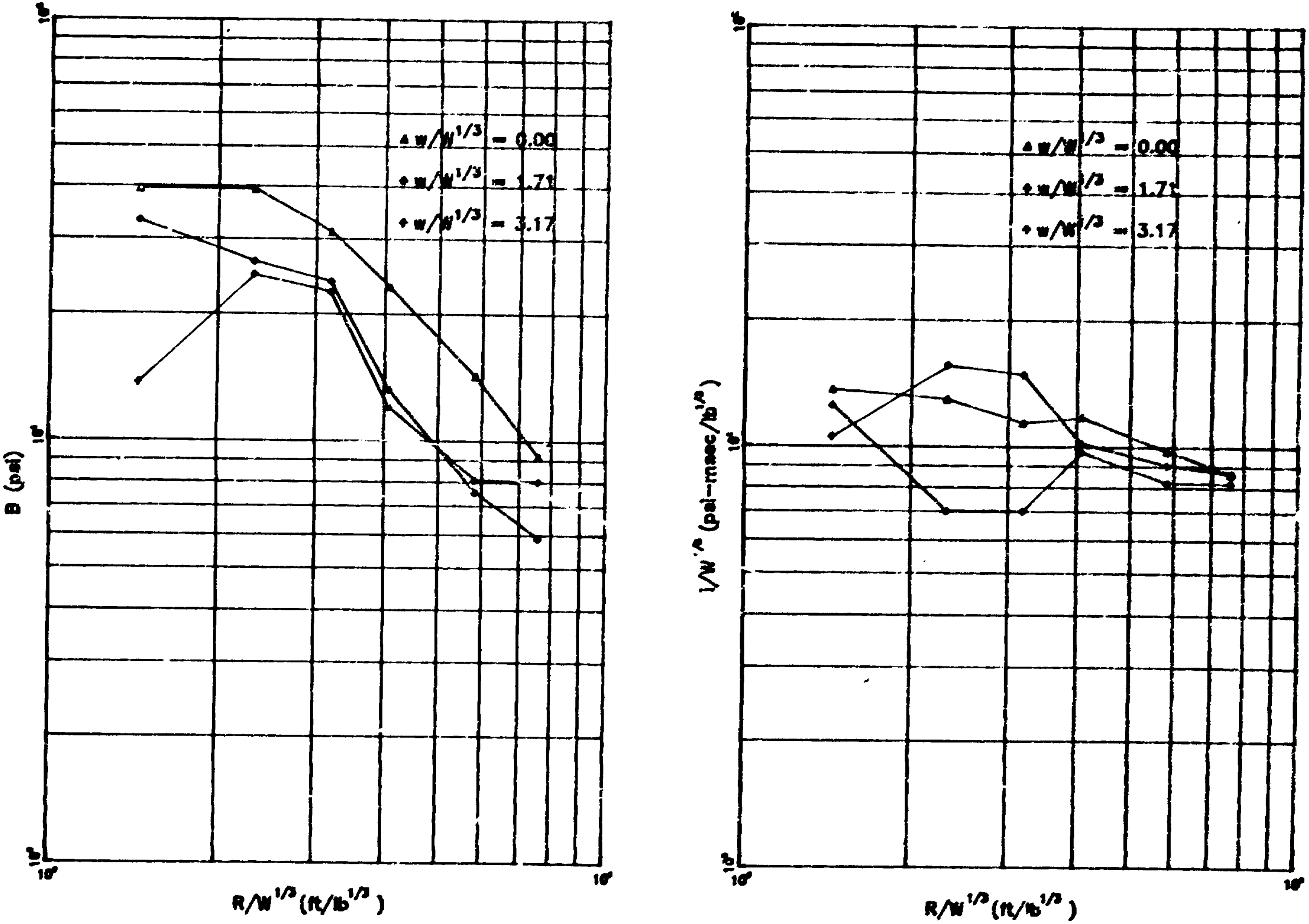

Figure 12. Preliminary design curves. Surface gages, wall with canopies, W_{C4} = 15 lbs.

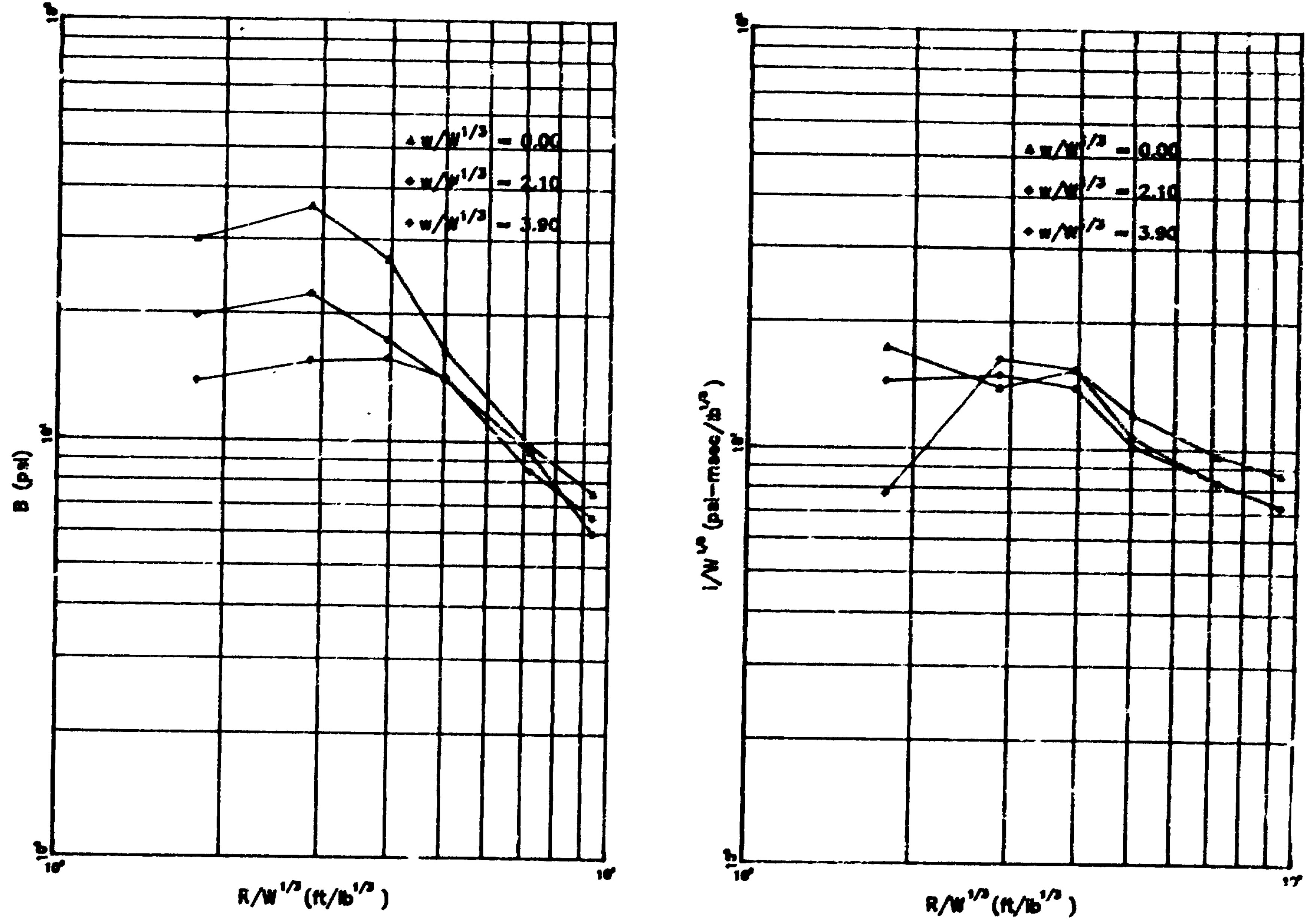

Figure 13. Preliminary design curves. Surface gages, wall with canopies, W_{C4} = 8 lbs.

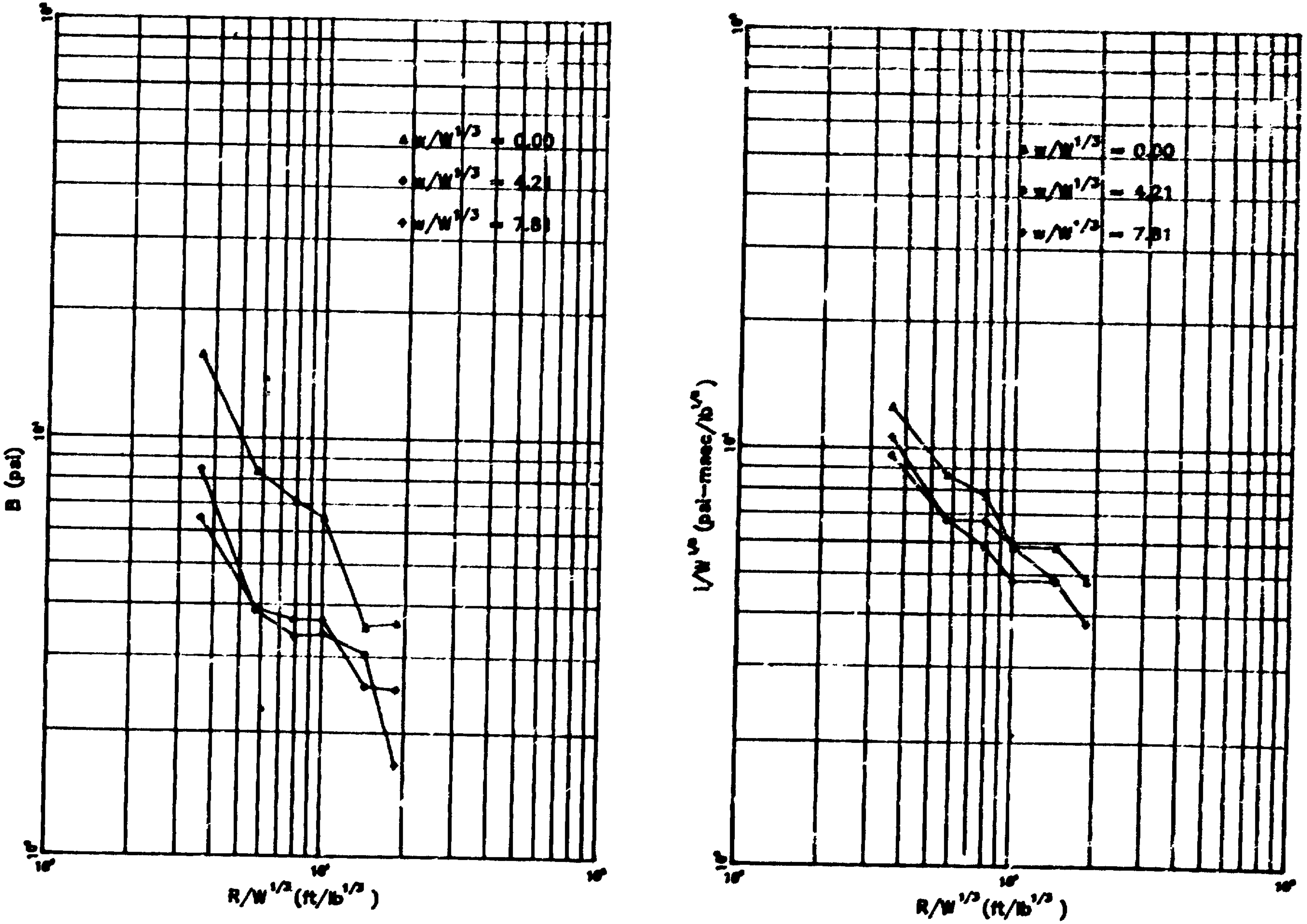

Figure 14. Preliminary design curves. Surface gages, wall with canopies, W_{C4} = 1 lb.

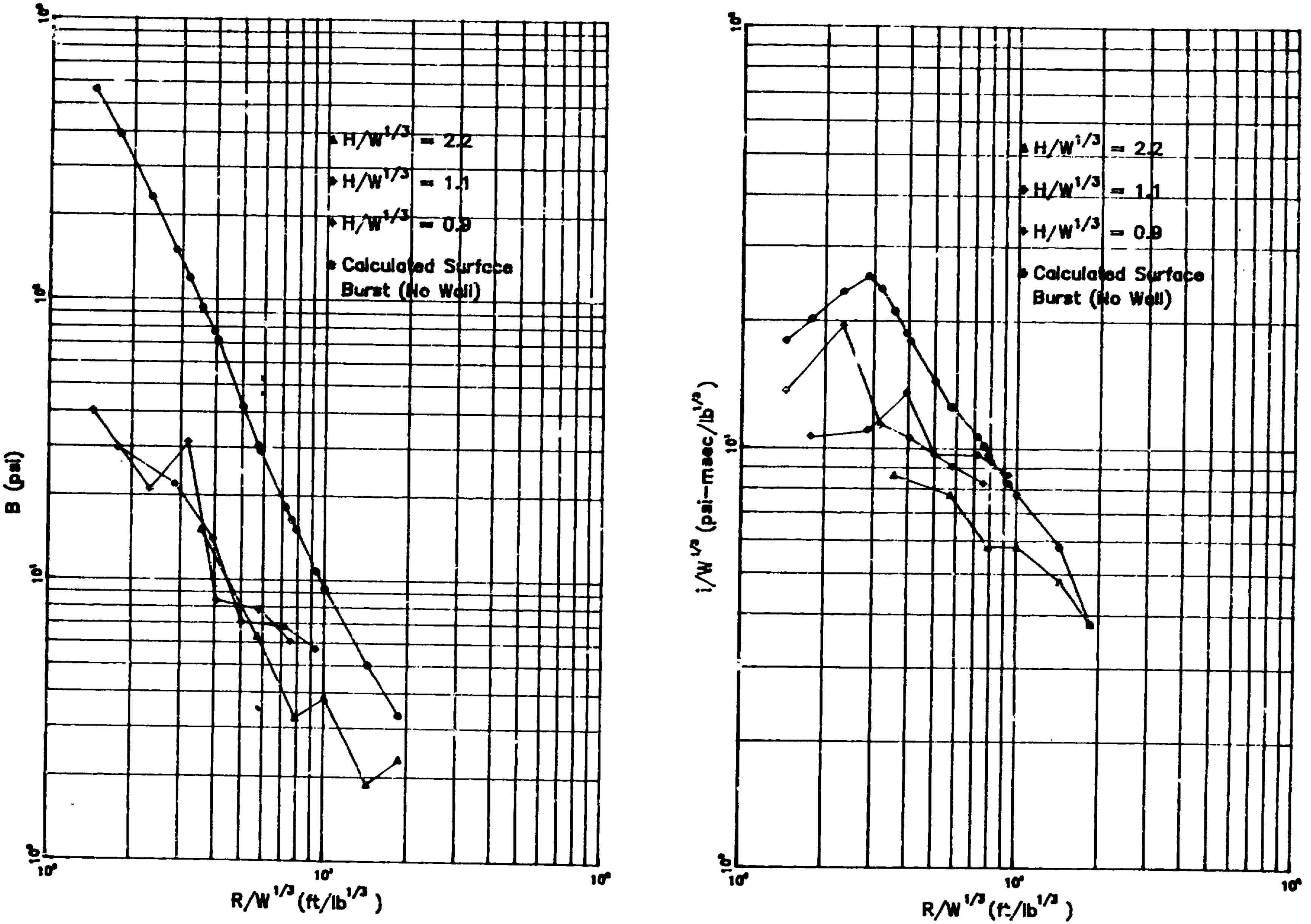

Figure 15. Preliminary design curves. Elevated gages, no canopy.

THE IMPACT OF EXPLOSIVE SAFETY ON READINESS
THE PRICE OF SAFETY

by

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at

Twenty-Second Explosives Safety Seminar
Anaheim, California
August 27, 1986

THE PRICE OF SAFETY

I appreciate the opportunity to speak to you today at this 22nd Explosives Safety Seminar. It is an honor and a privilege to address such a distinguished gathering. The diversity of the attendees, representing, as you do, United States military services, private industry, and academia as well as the counterparts from many other nations is truly impressive.

Safety, particularly explosives safety, is a very real and constant part of my duties. Among my responsibilities are the operation and management of AMCCOM's production base, the arsenal and ammunition plants, and the contracts we have with many of you at your industrial facilities.

are discussed

I was asked by COL Halstead to consider two contrasting viewpoints regarding explosives safety. First, safety as a stumbling block to readiness, and second, safety as an enhancer of readiness. are described

Let me ~~tackle first the proposition~~ that safety is a stumbling block to readiness. Safety is expensive. First there is the cost of the safety personnel themselves. In AMCCOM we have not only the government safety staffs, but also the staffs of the ~~contractors that~~ operate our ammunition plants. Second, are the facility and equipment costs. When dealing with explosives and the other hazardous materials that are involved in the production of ammunition we have costly electrical equipment approved for use in hazardous locations. Operations are often conducted remotely decreasing the production rate and increasing the cost of equipment required. Barricades and portions of buildings are constructed of specially designed steel reinforced concrete, and the buildings are separated from each other by distances that greatly increase transit time and costs, not to mention utility runs and energy costs. The equipment often has redundant controls, guards, and shields decreasing rate and increasing cost.

Safety reviews of project designs, hazard analysis of proposed or ongoing operations significantly delay the start of projects and frequently result in additional costs to address conditions noted during the reviews and analyses. Operationally, safety procedures are often elaborate, requiring adherence to step-by-step directions, permitting none of the "field fixes" or changes that can be used to speed up the work.

Safety is often not popular with the general public or with those concerned with the opinions of the body politic. Buffer zones for quantity distance are encroachments on what could be public lands used for recreational or other purposes. If you are in private industry, these real estate requirements have a very real dollar and cents impact. In developed nations, the contest between operational necessity and public desires or needs is never ending and never easy.

I could go on, but I believe you recognize what I'm saying and could add examples of your own. Safety is expensive and time consuming. In a period of shrinking resources, the need to commit every defense dollar to those activities that most enhance readiness is paramount. Often the questions must be asked. "What can we afford?", "What can be trimmed from this project?", "How can we speed it up?", or, again, "Is it too expensive?"

The answer to those questions, as they apply to safety, and the response to the proposition that safety impedes readiness is contained in the logical extension of the old saying, "Experience is the best teacher." Yes, experience is the best teacher. Her lessons are swiftly delivered and strongly etched on our memories. It is just that we cannot afford the tuition she charges. Tuition is paid in units of accidents. Accidents have surcharges of deaths, injuries, damages and mission degradation. Accidents are the price of short changing safety at various decision points in a process or project.

Each of us has our own accident reporting systems that record the costs of accidents, but many indirect costs never make these reports. Let me give you an example for which my people were able to supplement the normally recorded information. This accident was the February 1985 explosion in the nitration house of the batch type nitration system at our Radford, Virginia ammunition plant. Two of our people were killed and the nitration house was completely destroyed. Other personnel received more minor injuries and there was damage ranging from severe to mild to other facilities on post. The quantity-distance relationships adhered to resulted in the damage being no more severe than is normally associated with the separation distances. It is, however, sometimes difficult to explain to those less skilled in explosives safety than yourselves, that intraline distance only defines the degree of damage anticipated in the event of an explosion. It does not mean that damage will be limited to the structure in which the explosion occurs.

The officially recorded cost of the accident was $1,926,000 in property damages. Although no amount of money can compensate for the loss of life, for statistical purposes, the loss of a life is given a dollar value. Thus the direct cost of the accident was just short of $2 million in property damage and $350,000 in injury costs.

The accident was investigated by a select Army team of six military and civilian personnel. These individuals were assisted by three consultants from industry and universities and the now retired chairman of a previous board of investigation. An additional six individuals met with the investigation board for a shorter period. The period of the investigation extended from 6 Feb 85 to 19 Apr 85, although the board was not in continual session. This amounts to approximately $80,000 in salaries at government pay scales for the government investigation team and the supporting consultants. Transportation and per diem costs for the government members were approximately $24,000. Not included are any costs associated with the individuals who met with the board for shorter periods. Similarly, we do not have any means of estimating the impact on the organizations from which the board members were drawn. All had regular assignments that had to be accomplished by others in their absence.

An investigation of this magnitude requires considerable installation support. At Radford, a contractor operated facility, most of the support requirements were levied on the contractor staff. The contractor involvement included personnel in technical services in hazard analysis and testing ($71,000), engineering ($102,000), chemical process ($47,000), and maintenance ($600,000). Administrative support including $2500 in labor and materials in for photographic coverage and reproduction of the final report.

The repairs to the other structures, beyond the manpower cost I mentioned amounted to $96,000 for the materials. Considering the nitration building itself, it had a book value of $848,000, signifying that it cost about that in 1940, when constructed. To replace it in kind was estimated at $1,900,000. Re-examination of our needs and our desire to provide the best protection possible for our workforce, following studies of nitroglycerine facilities worldwide, has resulted in the design of a modernized facility costing nearly $10,000,000. This new facility will, of course, be much more than a replacement of the lost facility.

With this facility out of action, it was necessary to buy nitroglycerin and premix from commercial sources to stabilize production and employment. An additional $925,000 was required for the purchase and transportation of these materials. Despite these efforts to stabilize the situation, as many as 500 personnel were furloughed at various times following the accident.

There are additional costs, both tangible and intangible, that are more difficult to calculate accurately. These include the impact on the confidence of the workforce, our neighbors in the Radford community, and with the state and federal legislators, the lost production opportunity and the time value of money. Even without these areas of impact, the cost of accident is now over 4 million dollars, double the cost based on conventional measures.

I realize that not all accidents are of the same magnitude or consequences. Unfortunately, there is no fixed ratio between the consequences of an accident and what we are able to learn from it. We pay dearly for what we learn from the major accidents. Taking the Radford example, what would 4 million dollars have bought in terms of readiness? What is that in M483 projectiles? In RAAP (rocket assisted projectiles)? In small arms? (See viewgraph)

Balanced against the cost of this and other accidents is the cost of safety itself. When I briefly examined the impacts of safety on readiness earlier, many areas of cost were indicated. Collectively, these costs could be considered to be the preventive costs. I had intended to contrast the cost of safety with the cost of accidents. I am unable to do so, and upon reflection, I'm pleased I cannot. The cost of accidents can be specified, if only imprecisely as in the example above. Safety, however, is so thoroughly ingrained in the structure of AMCCOM, that only in certain areas can the cost of safety be separated from the overall cost of performing the mission. The cost of the AMCCOM safety staffs can be determined precisely. The cost of their activities, in designs for projects for new or modified facilities, could be extracted from the over all project cost only with great difficulty. I can, with precision, list the cost of each manufacturing methods and technology project (MMT) that was accomplished solely to answer a pressing safety need, but I cannot assess the time spent by my subordinate commanders and managers on safety, and yet that is a chargeable responsibility for each. I can tell you that AMCCOM is pressing ahead in exploring new areas to increase the expertise in safety. We are now looking at virtually every accident involving energetic material that results in measureable damage or any degree of injury. We are in the process of establishing a special center within the command to be a special safety resource to serve our production base installations. We are conducting special reviews and studies of phenomena related to explosives accidents and are sending special teams to investigate a greatly increased number of accidents. This year saw the first of a series of projects specifically oriented toward the elimination of deviations from regulatory safety requirements (we have already cut these by more than half) and to remove the man, our operating personnel, from exposure to explosives. These are tough challenges, but we have begun.

I cannot put a specific cost on these initiatives, or many of the other aspects of an aggressive safety program. Nor do I have to. AMCCOM has answered the question - "Can we afford safety?" - with a resounding - "Yes."

I would like to leave you with a challenge. It seems that after too many of our accidents we find that the cause was a relatively simple thing or series of simple things. In other cases, regretably, the cause may be found to be literally "dumb" mistakes. We use the techniques of hazards analysis to examine our processes and equipment. We train both supervisors and employees to recognize hazards and to follow procedures. We repetively inspect, review and test. Then we do it again. Still, although with decreasing frequency, we experience accidents.

What can be done to change that old Pennsylvania Dutch proverb, "Old we get too soon, and smart we get too late."?

NAVAL ARMAMENT DEPOT FOR THE ROYAL AUSTRALIAN NAVY

by

Commander W. BURROUGHS, RAN
Project Director Base Development

presented by

Brigadier J.G. HUGHES, AM
President - Australian Ordnance Council

P60763

ABSTRACT

1. For many of you not familiar with life 'Down Under' I will explain a little of our geographic location twixt Indian and Pacific oceans. Australia is a large country somewhat similar in size to the continental portion of the United States, however, our population is a sparse 15 million mainly concentrated around the south-eastern seaboard. Accordingly our limited defence forces and in particular the Navy have a vast area to cover. Traditionally the Navy has operated from its main base in Sydney, however, strategic and operational considerations now dictate that this operating pattern should be reviewed. Our Prime Minister, Mr Hawke, made an announcement in November last year on the planned relocation of Naval armament facilities from Sydney to Jervis Bay by 1992 and for an examination into the relocation of the fleet base, submarine and mine warfare bases over the next 20 years. He also emphasised the need to build up ship numbers in Western Australia which may give rise to a Two Ocean navy concept.

2. It is against this background that the Royal Australian Navy is about to embark upon a major construction project for a central ammunition depot to replace existing facilities in eastern Australia. These will be used for a variety of storage, test and maintenance functions for RAN conventional ammunition of all types. The facilities will embrace latest design criteria with building being undertaken by the Department of Housing and Construction.

INTRODUCTION

3. The history of the storage of munitions on Australian soil is as old as recent history of the country. The first fleet was led by HMS SIRIUS a frigate of 540 tons, she was fitted with 6 carronades and 14 six pounders. Shortly after her arrival in Sydney Cove in 1788 eight of the six pounders with 24 rounds of shot for each, plus 20 half barrels of powder were landed at Dawes Point and held there in a redoubt. This is now the site of the southern pylon of the harbour bridge. The first permanent magazines ashore were established at Goat Island in the early 1800's and a powder magazine was constructed at Spectacle Island in 1865.

4. In the 1870's negotiations which had long continued between the Admiralty and the Colonial Government concerning the site for a Naval depot had reached an impasse, which centred upon the desire of the Naval authorities to have Garden Island but Commodore Goodenough, who was then

in command of the Australian Station, reported that the inhabitants of Sydney would strongly object to the stowing of powder so near to the town, and he advised the retention of the Naval magazines on Goat Island.

5. It was not long, however, before the Navy found the need for additional storage and the first explosive storehouse was built at Homebush Bay (RANAD NEWINGTON) in 1896. There was gradual development of this site with substantial works occuring during WWII, which mainly centered around the storage of ammunition for the American and British Pacific Fleets. In fact a number of the magazines are of USN construction. Also developed during WWII was the RAAF Central Ammunition Depot which is shared with Navy as RANAD KINGSWOOD.

WHY MOVE

6. The present arrangements for ammunitioning and deammunitioning ships in Sydney through Kingswood, Newington and Spectacle Island, utilising water, road and rail transport have many inadequacies. These are time consuming and labour intensive and, as a result uneconomic. There are also many difficulties in meeting the safety requirements for the transportation and storage of explosives. The facilities, especially those at Newington, are antiquated and in need of replacement.

7. There is an overall desire to remove naval activity from the Sydney foreshore where this is incompatible with other forms of development. For many years strong pressure has been exerted by State and Local Government for Navy to move from Newington. Pressure to move from Kingswood has been minor, but must increase as the metropolitan area creeps inevitably westwards.

WHY JERVIS BAY

8. Studies for the relocation of Naval armament facilties have been conducted over a number of years and all have concluded that the only suitable site that is readily available on the NSW coast is at Jervis Bay. A zone planning exercise has also been undertaken to consider all RAN long term plans in the Jervis Bay region to ensure that the armament depot proposal is compatilbe with other requirements.

P60783

9. An essential feature is for the depot to be within reasonable transit of the refitting and support facilities that exist in Sydney, as it is necessary to disembark ammunition outfits prior to ships entering refit or routine docking. It is also desirable for the depot to be located close to the main Naval exercise areas thus avoiding long transits and loss of valuable exercise time. Until recently the RAN has not had the ability to conduct underway replenishment of munitions and even with the commisioning of HMAS SUCCESS this will remain a limited capability.

10. The greatest single factor in planning has been finding a site for the explosives wharf. Owing to the relatively large area required to meet quantity distances and the need not to compromise other possible developments the only suitable site for a wharf appears to be at Green Point on the Beecroft Peninsula. Siting of the depot posed another set of problems and 9 potential sites that could link with the wharf were considered. A preferred site clear of all major constraints has now been selected in the Currambene State Forest.

THE REQUIREMENT

11. The project seeks to establish a wharf to cater for all HMA Ships and commercial vessels up to 30,000 DWT. The size of the depot has been predicted upon the forecast composition of the fleet for 1990, in catering for ship's outfits plus support outfits and practice allowances. The first stage of development involves the closure of Newington and at a later stage the transfer of missile and torpedo maintenance from Kingswood. The total area required to accommodate these facilities is:

wharf	2450 Ha
depot	1500 Ha

12. The requirement is based upon two assumptions.

a. The RAN will continue to maintain its main bases, dockyards and refitting facilities in south-east Australia, and centralise stockholdings in this area.

b. The project will proceed with the co-operation of the NSW Government, and that additional land requirements will be purchased by the Commonwealth.

SITE CONSIDERATIONS

13. The site for an armament wharf at Green Point is fortunately on Commonwealth owned land. The area mainly comprises unused bush, however, being on the crowded coastal belt there are many environmental issues. The region includes a number of diverse plant communities consisting of rain forest, mangroves, swamp and heath. The layout and construction will therefore need to take account of the ecological and hydrological aspects of the area. The entire Beecroft Peninsula has been listed on the Register of the National Estate, accordingly the proposal will require consideration by the Australian Heritage Commission as well as the Department of Arts, Heritage and Environment. An environmental impact statement is therefore required and consultants are expected to be commissioned for this purpose in September this year.

14. From the functional viewpoint colocation of the wharf and depot is highly desirable, being both operationally efficient and cost effective. Site options 1 and 2 for the depot are on Commonwealth property on the Beecroft Peninsula, however, the quantity distances involved border the village of Currarong and the Naval bombardment range. There is little room, therefore, for expansion and for safety reasons it is prudent to move the depot from Beecroft.

15. All lands adjacent to the wharf of sufficient area to accommodate an armament depot have been considered and a number rejected for environmental reasons or because of incompatibility with possible future developments. The first suitable area that is clear of all known restrictions is some 16 Kms from the wharf. While distance represents a disadvantage, this site is believed to provide the best solution to the overall requirement. As the depot site embraces State Forest, Crown Land and public property, negotiations are underway between the Commonwealth and State Governments for the eventual transfer of this land.

POLITICAL AND PUBLIC PRESSURE

16. As Commodore Goodenough observed there is no great enthusiasm amongst the general poplace for armament depots. This is despite the fact that such facilities are benign in their scope of activity and furthermore are likely to preserve the pristine nature of large tracts of land in its original state. It is of interest that the NEWINGTON armament depot contains the only significant stand of trees in the central western suburbs of Sydney that can be said to be representative of the area at the time of the first white settlement. Naturally there is public concern to safety through accidental explosion and the creation of a possible target. Armament facilities should, therefore, be sited well clear of habitation and public property. This is assured at the proposed depot site and as no explosives will be permanently retained on the wharf, the problem is of a temporary aberration in that locality.

17. The project team has been conscious of public opinion and political nuances. There are benefits to the local area which must be capitalised, these are mainly economic in terms of increased employment opportunities, the injection of additional income to the local community and the potential market for the infrastructure to support the construction and operational phases of development. Social benefits will also flow in improved transportation links and the social, culteral and educational services required to cater for an enhanced population base. A public information campaign has been developed and there are regular visit to discuss issues with the local residents.

CONSTRUCTION AND COMMISSIONING

18. As a preliminary to the major construction it will be necessary to conduct substantial advanced works comprising:

External Services

upgrade or replace approximately 20 km of public road

provide electrical power

provide mains fresh water

Internal Services

internal roadworks

reticulation of services

surface drainage

sewerage drainage

sewerage facilities

security fencing

fire breaks

19. The initial stage of construction will comprise a wharf, missile and torpedo storage, explosive and non-explosive storehouses for conventional ammunition, explosive and general engineering workshops, a container handling area and administration building. The user requirements have been validated against experiences gained through studies from overseas sources. Theses studies have demonstrated a need to standardise designs, accordingly US criteria has generally been adopted as a design philosophy and a technical support case has been sought through the USN to provide oversight to the design. However, there are certain home grown characteristics to be considered; for example the workshops are likely to be constructed on rocky terrain, therefore tests will need to be conducted to ensure inter-magazine safety distances meet our specifications.

20. The new facilities which are due to commission in 1992 will be subject to intensive scrutiny through an Environmental Impact Study and by fhe Parliamentary Works Committee prior to Government approval. The Jervis Bay Armament Depot project will provide contemporary facilities and through considerable economics of operations make better use of limited resources.

P60783

TRAINING FOR SAFETY IN THE MILITARY ENVIRONMENT
PRESENTATION BY BRIGADIER M C OWEN, DIRECTOR OF LAND SERVICE AMMUNITION AND CHIEF INSPECTOR OF EXPLOSIVES FOR THE BRITISH ARMY
FOR AMERICAN TRIP

1. The military environment places exacting and often conflicting demands on ammunition and explosives and on the men who handle and use them. In peacetime, large stocks must be maintained to allow for rapid mobilisation when required, but financial constraints permit only a small proportion of these to be turned over during training. The remainder are expected to be stored for several years, often in extremes of climate, and yet remain safe for immediate use anywhere in the world without detriment to their performance. At all times the stocks must withstand transportation by land, sea and air, by a variety of unforgiving means. In combat they must endure small arms fire, explosions, high velocity fragments, chemical attack and a wide spectrum of radio frequency hazards, yet still function perfectly when required. At all stages, safety is of paramount importance and, even in combat conditions, it is preferable that the ammunition kills foes not friends.

2. Such an environment clearly demands high standards of safety among the soldier technicians responsible for the ammunition throughout its Service life.

3. My appointment as Director of Land Service Ammunition and Chief Inspector of Explosives for the British Army makes me responsible for the safety, proof, test, inspection, repair and disposal of our ammunition throughout its Service life, and often beyond. I, and members of my staff, represent the Army in the ammunition technical field on tri-Service committees and working parties which meet with other agencies such as the Explosives Storage and Transport Committee, known as ESTC, and the Defence Explosives Safety Authority, DESA. The latter provides the interface between the Health and Safety Executive – the authority for enforcing the Health and Safety at Work Act, and the Defence Services. My responsibilities are exercised through the Ammunition Technical Officers (ATO) and Ammunition Technicians (AT) of my Corps – the Royal Army Ordnance Corps, and by the publication of Ammunition and Explosive Regulations (A and ERs) which provide guidance and direction to my technical personnel.

4. Everyone who handles or uses ammunition has a responsibility for safety. For example, a tank crew must follow certain laid-down gunnery drills lest they commit an indiscretion. However, this presentation will concentrate on skills within my area of influence; the training of our Ammunition Technicians. Our Ammunition Technical Officers, commissioned officers, receive similar training but, as it is the Ammunition Technician the non commissioned technician, who lives with ammunition throughout his career, I will concentrate on him.

5. Ammunition Technicians, and indeed Ammunition Technical Officers, receive their professional technical training at the British Army School of Ammunition in Warwickshire. The School also provides a wide range of other courses for both technical and non-technical personnel covering the full spectrum of ammunition duties from Ammunition Familiarisation courses for fighting units, to seminars for the operators of sophisticated equipment in operational bomb disposal teams. Whatever the course of training, the nature of ammunition and explosives demands a constant emphasis on safety throughout. Students from some 88 countries have attended courses at the School. The voices of American students are heard throughout much of the year.

6. The aim of all training is to bring a student to a desired standard of job performance by instruction and practice. Before designing any course of instruction it is therefore essential to analyse the job to be performed and specify the standard to which the student must be trained. At the School considerable effort is put into ensuring that the right calibre of student is selected for Ammunition Technical training and that students then achieve the training objectives set out for each aspect of the course. Where an objective is directly concerned with safety, failure to meet the standards laid down means failure on the particular phase of instruction, so that the student must be retested or rejected.

7. I will now proceed to look more closely at the work of the Ammunition Technician and the training required to prepare him for this work throughout his career.

8. The technician's work covers 4 broad areas; the storage and movement of ammunition whether in depots or units or in the field; the surveillance of ammunition to ensure safety during its storage and handling and its correct functioning when required for use.

9. To prepare him for this wide range of responsibilities the Ammunition Technician must have a thorough understanding of the theory of explosives and the principles of ammunition design. He therefore spends the first 5 weeks of his basic Ammunition Technician course at the Royal Military College of Science in Wiltshire, the Army's University, where he gets instruction in the basic scientific principles of ballistics, explosive chemistry, polymer science, mathematics, nuclear physics, metallurgy physics, electronics and mechanical design. Student Ammunition Technicians attending this phase of the course are the only non-commissioned students to receive instruction at the College which is otherwise a seat of learning for officers and equivalently graded civilians. I should point out that our Ammunition Technical Officers undergo a far more in-depth study of these subjects over a period of 6 months at the College before moving to the Army School of Ammunition to complete their technical training.

10. On arrival at the School the student Ammunition Technician spends several weeks in the classroom, studying the make-up and functioning of every nature of Land Service Ammunition. This includes Guided Missiles currently in service, including Milan. Instruction during this period is punctuated by regular examinations to ensure that all essential safety factors have been thoroughly assimilated and the student is able to use the volumes of technical manuals available to him as and when required. However the student is not confined entirely to the classroom during this phase. Once the essential theoretical knowledge for each nature has been understood he spends time in the School's own Ammunition Process Building, known as workshops, inspecting and handling the live ammunition under the very watchful eye of experienced instructors.

11. Having thus learnt to relate his scientific education to the practicalities of ammunition, the student goes on to learn the regulations and principles governing the storage and movement of ammunition and the procedures for in-service proof. This is followed by a 5 week period of practical ammunition and repair in the workshops. Instruction during this phase is necessarily detailed because it is in the workshops of major ammunition depots that the young technician will usually spend the first few years of his service.

12. To complete his first course of technical training the student spends one week learning the basics of EOD procedures on demolition and burning grounds, and a further 2 weeks learning to handle the explosives and equipment he will meet as an assistant on a bomb disposal team.

13. Before he returns to the School to attend the next stage of his technical training, he will have gained at least 2 years practical experience and the rank of Corporal. It is essential to understand that a most important aspect of training for safety is leadership training. It is vital that, in performing a potentially dangerous task, the man in charge is in firm control of the situation. Otherwise, short cuts will be taken, vital safety factors will be overlooked and accidents will happen. The Ammunition Technician is first and foremost a soldier, so during the first 2 years, and indeed later years he will undergo regimental training to develop his leadership skills. This, combined with expertise of progressively higher levels of responsibility, ensures that he is capable of control in a safety aware environment.

14. After this initial 2 year period he will attend his 12-week Technical Upgrading Course which will build on this experience and expand his knowledge of all aspects of his trade. The instruction is geared towards the management of surveillance and repair tasks, and supervision of demolition and burning grounds, and will prepare him well for the responsibilities he will meet as a Sergeant Ammunition Technician. Before qualifying for promotion he must also qualify as an intermediate bomb disposal operator and gain certificates of military education and proficiency. Although this ends his formal technical training he will return for updating, briefing or special training, including advanced bomb disposal, whenever his assignments require this. He is also likely to join the staff of the School as an instructor at a later date.

15. From this brief outline of Ammunition Technician training it should be clear that we cannot produce instant ammunition experts. Over the years our technicians have acquired an excellent reputation for expertise and safety. Our training system is geared to ensure that this reputation will be maintained by future generations of technicians. The system is founded on 4 main pillars; personnel selection, comprehensive instruction, constant monitoring and progressive training and I shall consider each briefly in turn.

16. First, personnel selection. It is essential to ensure that the right calibre of student is selected to undergo training. Academic prowess should be tempered with sound practical ability and a good measure of commonsense and level-headedness. No student can begin Ammunition Technical training at the School unless he has been recommended as suitable after a searching series of psychometric, pratical and academic tests.

17. Second, comprehensive instruction. Students must be given a detailed theoretical understanding on which to base their knowledge of regulations and procedures. Rigid drills must be taught where these are essential for safety – on the demolition ground for example – but the student must be fully aware of why they are necessary.

18. Third, constant monitoring. Instruction should be progressive, starting with the theory, progressing to practice and inert stores where possible, and finally on to practice with live ammunition. Student performance must be closely monitored at each stage to identify any weaknesses before they can become a danger. This can only be achieved by regular examination and practical assessment, often with a one-to-one ratio of instructors to students. This process is time consuming and manpower intensive but the consequences of inadequate monitoring are potentially disastrous.

19. Finally, the training given should be progressive throughout the man's career, with ample time allowed to reinforce the instruction with practical experience on the ground.

20. This progressive pattern of career and training development ensures many advantages including the technician building and developing sound technical knowledge, which is not merely theoretical but is reinforced at every stage by practical experience, gained both during and after training. We believe our system succeeds in achieving the right balance of academic and practical skills. Also, the finished product is not just a technician, but also a leader. His training and experience in organising and controlling tasks combine to ensure that the non-commissioned officer Ammunition Technician and, indeed the Ammunition Technical Officer have the ability to command a situation, execute a thoroughly professional job, ensure a safety conscious environment, reduce the chances of accidents and produce a man who since 1969 has received 230 awards for gallantry and distinguished service.

21. Our training may seem to be manpower intensive and, therefore, costly. It would be possible to train the same number of men with less resources but we give such a high priority to the maintenance of safety standards in the military environment that we are not prepared to take short cuts in training. Gentlemen, I am sure you will agree, there can be no compromise on safety, and we certainly approve the product of our system – he's done us proud.

KLOTZ-CLUB TESTS IN SWEDEN

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presented at the

22nd Department of Defense Explosives Safety Seminar
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CONTENTS

SUMMARY

In the paper the objectives of the Klotz-Club tests performed in Sweden are described. The main purpose of the tests is to give data on debris and fragment throw from detonations in ammunition storages in rock. The installation is described and results from four of the tests are given.

1. INTRODUCTION

The Klotz-Club has its origin in 1966 when a group of people discussed the possibilities of reducing the blast effects from accidental explosions in underground ammunition magazines with a large closing device, a block (in German: Klotz).

Theoretical and experimental studies were followed by a successful "full scale" proof test in 1973. The - by that time four - participating countries decided to continue a fruitful cooperation within the fields of explosives safety. A number of efforts have been made within the frame of the Klotz-Club, cfr /1/.

In October 1985 the now seven participating countries - the Federal Republic of Germany, France, Norway, Sweden, Switzerland, United Kingdom and the United States - decided to make a test series in a joint installation to be built at ArtSS, Älvdalen, Sweden. The objectives of the tests were to give data on

- debris and fragment dispersion
- blast propagation
- influence of geometry on debris flow and blast propagation
- groundshock effects
- TNT-equivalence for artillery rounds
- degrading effects of detonations on e.g. shotcrete.

For details see /2/.

2. BACKGROUND

The hazards in the vicinity of an ammunition storage in rock are mainly from blast, fragment and debris and from groundshock.

The airblast from a detonation in an underground installation is given in design manuals e.g. the Swiss TLM 75, /3/.

The distance, d, with the overpressure, p, outside a tunnel with the overpressure in the entrance, p_0 - presuming that the rock cover does not break - is

$$d = 0.7\left(\frac{p_0}{p}\right)^{0.9}\cdot D$$

where D is tunnel diameter in the entrance.

The results from this formula can be compared with test results e.g. /4/ and /5/. Especially for low pressure levels the Swiss formula gives conservative values as can be seen in figure 1. This is due to the fact that the exponent 0.9 has been chosen instead of the theoretical value 2/3, cfr /6/. The test results in /4/ are condensed into the formula

$$d = 1.17\left(\frac{p_0}{p}\right)^{0.74}\cdot D.$$

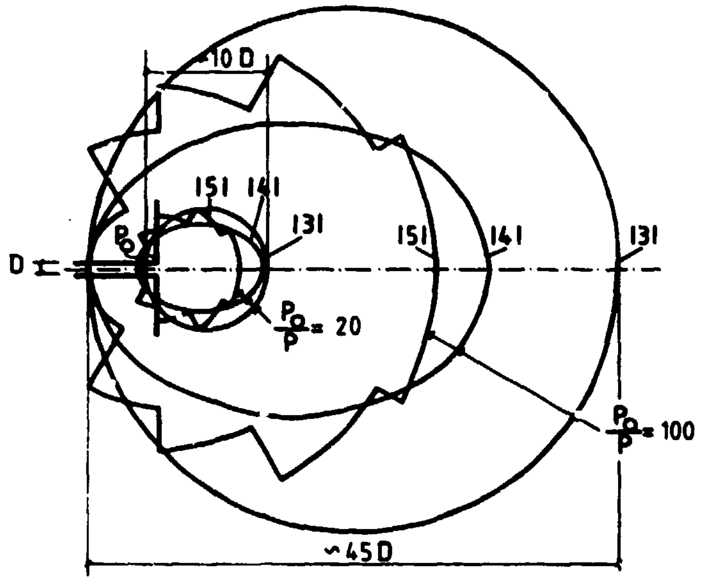

Figure 1. Comparison of different formulas for the overpressure outside a tunnel entrance from /3/, /4/ and /5/.

For debris and fragment throw very few reliable data exist that can be used for design purpose or risk analysis.

Again, the TLM 75, /3/, has stipulated hazardous zones outside the tunnel entrance basically according to figure 2.

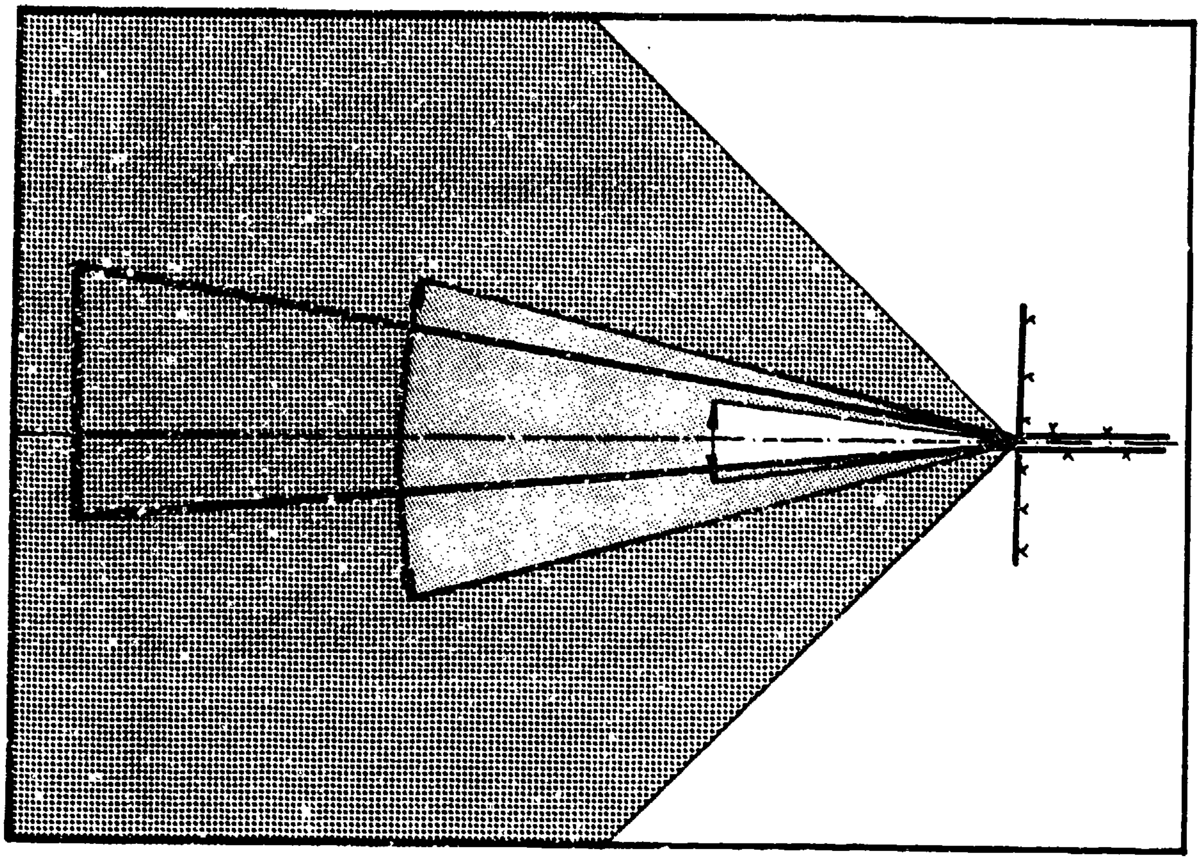

Figure 2. Lethality zones outside an ammunition storage due to debris and fragments according to /3/. Principle.

The hazardous area due to blast can be predicted with a higher degree of certainty than that due to debris and fragments. Also model tests for studies of blast propagation can often be made at low costs and give accurate results. Model tests have even been permitted as a basis of design for some magazines when it comes to blast, cfr /5/.

For debris and fragment dispersion models can not be used easily for predictions due to substantial scaling problems e.g. air resistance and gravity.

Especially, when a more sophisticated concept for desing codes, like risk analysis, is to be adopted a more comprehensive database on debris and fragment throw is mandatory.

The main objective of the initial tests at the installation was to study debris.

The velocity of debris can be calculated, theoretically, e.g. according to the model in figure 3.

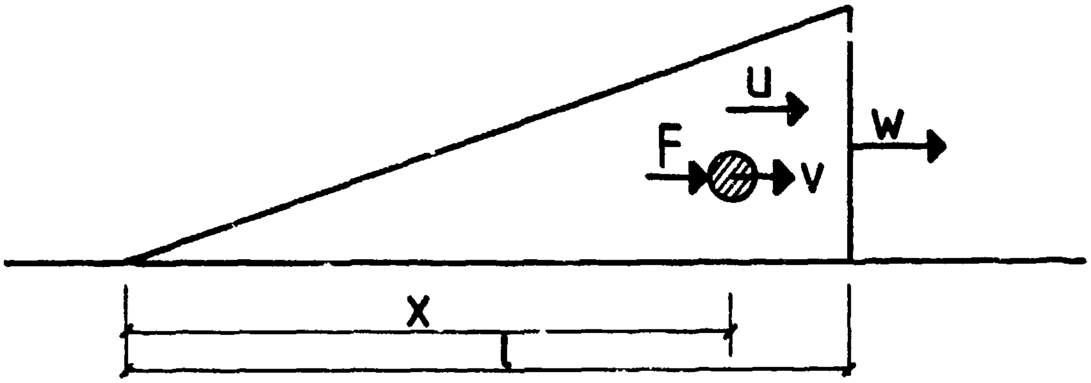

Figure 3. Simplified model for calculation of debris velocity.

The dynamic pressure, q_t, is calculated from

$$q_t = \frac{1}{2} \rho_t (u_t - v_t)^2 \quad \text{where}$$

air density

u air particle velocity

v debris velocity

For debris

$$m \cdot \dot{v}_t - \frac{A\rho_t}{2} \cdot C_D (u_t - v_t)^2 = 0 \quad \text{where}$$

C_D drag coefficient

A drag area and

m mass.

A solution of this equation has been used in a computer program for the precalculations of debris velocities, /7/.

3. INSTALLATION

As the main objective with the installation was to make multiple tests with debris a site had to be selected where large amounts of explosives could be detonated without impairing the community, where competent rock with adequate rock cover could be found and at the outside of which a surface suitable for collecting fragments and debris could be arranged.

This led to the shooting range at ArtSS, Älvdalen, Sweden, very close to where the original large Klotz-Club test was made in 1973.

The rock at the selected site consists of porphyritic granite, poor in puartz, /8/.

Outside the entrance cutting a surface from which debris and fragments could be collected was made. The area in the form of a sector was close to flat up to 150 m from the entrance and then steeper to form a target area in total more than 300 m from the tunnel.

Figure 4 debicts the geometry outside the installation.

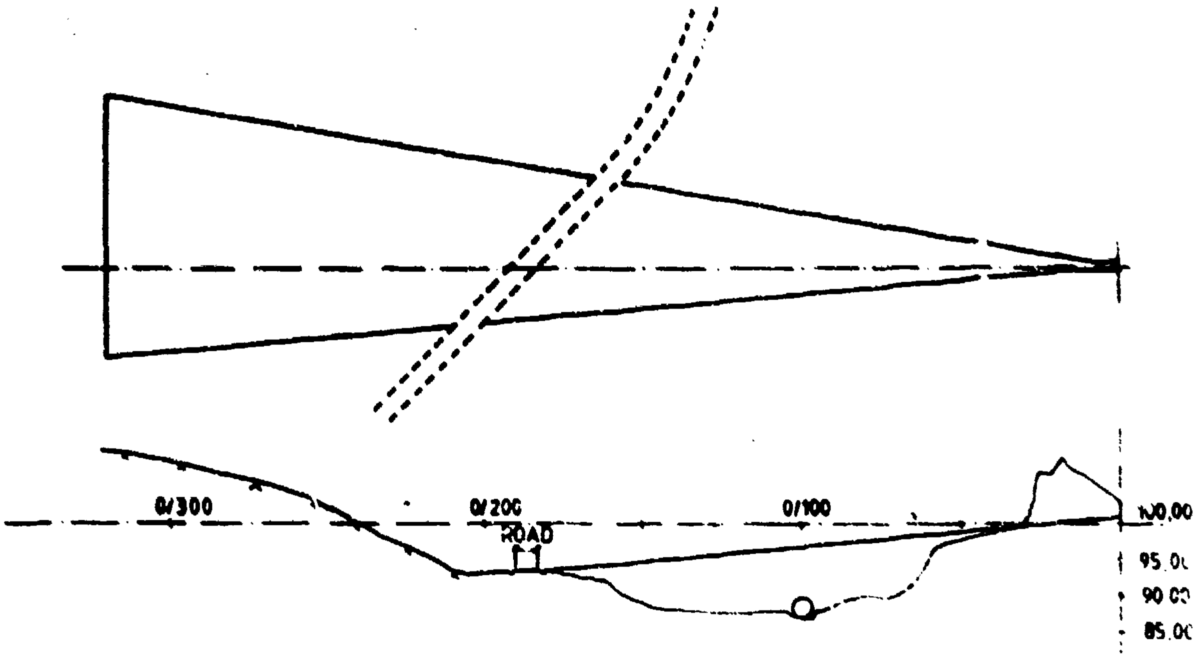

Figure 4. Geometry at the test site.

The tunnel in the rock was made with a crossection of 6.3 m^2. The walls were shotcreted. In the end of the tunnel was a chamber with a crossection of 12 m^2 and a volume of 300 m^3 e.g. a length of about 25 m. In 45° to the tunnel another tunnel with the same crossection was built. At the end of one end of that tunnel a chamber 17 m long with a volume of 200 m^3 was made. The other end of that tunnel was made 10 m long with the purpose of collecting debris and fragments coming out of the 200 m^3 chamber.

The tunnels and the chambers were bolted. The entrance part was made of reinforced concrete to ascertain that the geometry of the entrance would not change during the test series. Also to facilitate comparison with other test data a well defined geometry was needed.

The installation was made during the winter and early spring, 1986.

4. MEASUREMENTS

Measurements were made of blast, debris trajectories and groundshock. The groundshock measurements will not be given in this paper, however.

The blast was measured in the chambers, on different locations along the tunnel and outside and even above the installation. As the dynamic blast pressure is of interest e.g. for the studies of the drag forces on ejecta not only the static pressure was measured but - in front of the tunnel where it was significant - also the stagnation pressure. The placing of pressure gauges is shown in figure 5.

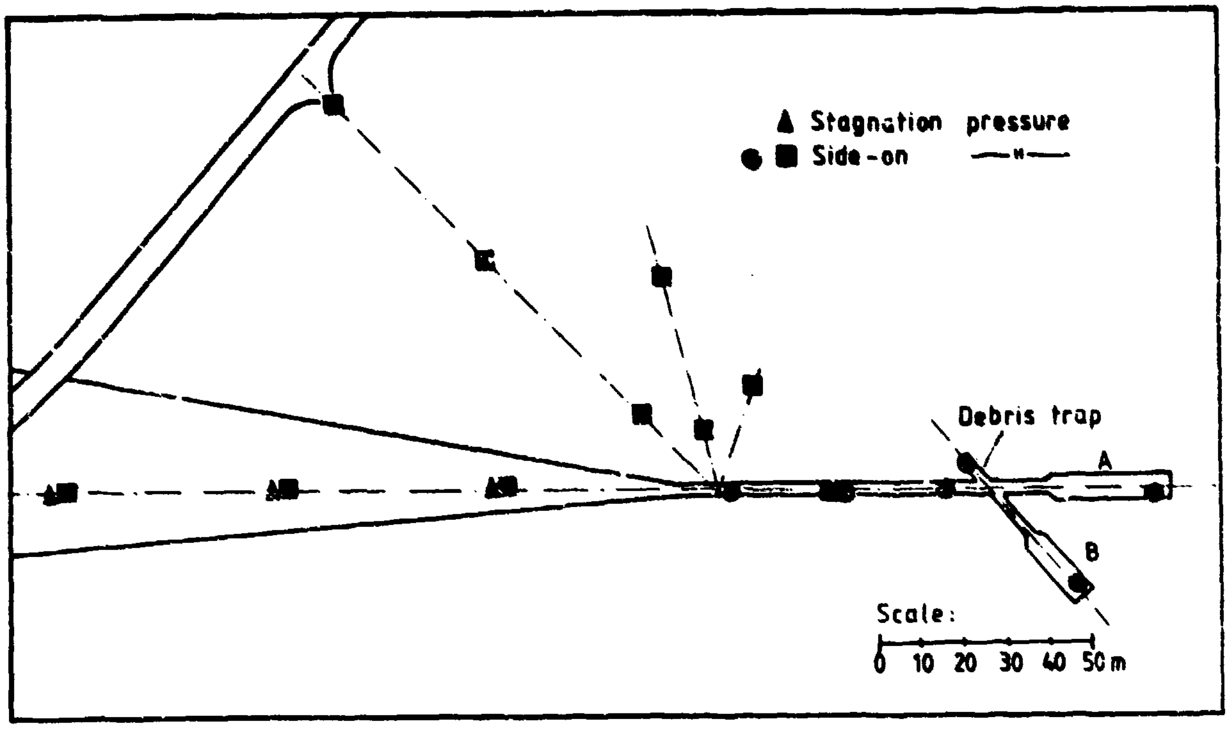

Figure 5. Blast measurement points.

To facilitate the measurements of the trajectories of the ejecta the area outside the tunnel was prepared with timber logs laid down perpendicular to the tunnel axis at 10 m distances across the sector and vertical poles for reference placed along the tunnel axis.

High-speed cameras and videocameras were placed perpendicular to and along the tunnel axis as can be seen in figure 6.

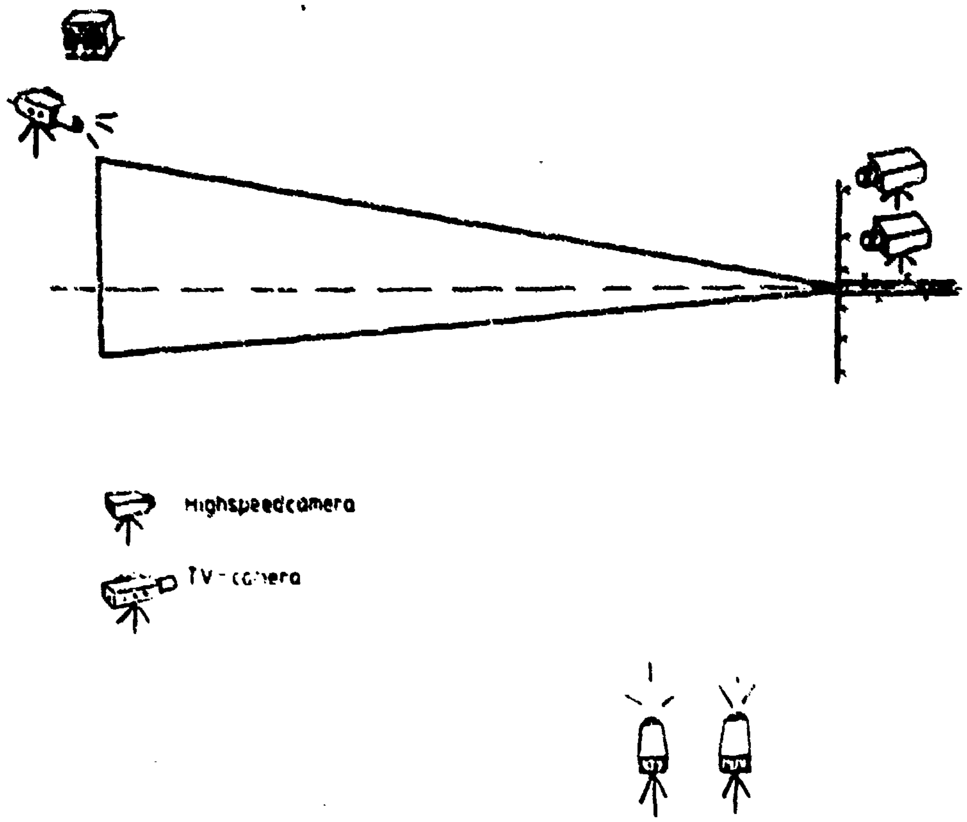

Figure 6 Highspeed cameras and TV during the test. The cameras along the tunnel axis were used only in tests 1-3.

5. TEST EXECUTION

The initial test program comprises six tests:

- 1. 10 kg TNT in chamber A
- 2. 10 kg TNT in chamber B
- 3. 1000 kg TNT in chamber A
- 4. 1000 kg TNT in chamber B
- Artillery rounds with net explosive weight 1000 kg in chamber A
- Ditto chamber B

Of these the first four will be commented subsequently. The last two tests in the program - among other things to give data on fragment dispersion and on TNT-equivalence - will be described in another paper.

The tests 1 and 2 mainly for calibrating purposes were made with the charge placed in the middle of each chamber. No debris was included in these tests and only blast measurements in the tunnel system and just outside the installation were made.

During the tests 3 and 4 1000 kg of TNT in the shape of a cubicle was placed in the middle of the chambers respectively.

Artificial debris in the shape and with the mass approximately like the artillery rounds for the final two tests were used. These debris were 680 mm long 160 mm diameter steel pipes filled with concrete. The mass was 47 kg.

These tubes were placed in the chamber standing on the floor behind the charge (4 of them) and lying and standing in front of the charge on the same level (16 of each). In the tunnel system pairs of cylinders were placed on the floor on the three locations were pressure gauges were installed. At test number 3 a pair of cylinders was also placed in the short access tunnel to the chamber.

Spheres of reinforced concrete approximately 110 mm in diameter (mass appr. 2 kg) were placed on top of the cylinders in the tunnels.

Figure 7 shows the location of the artifical debris.

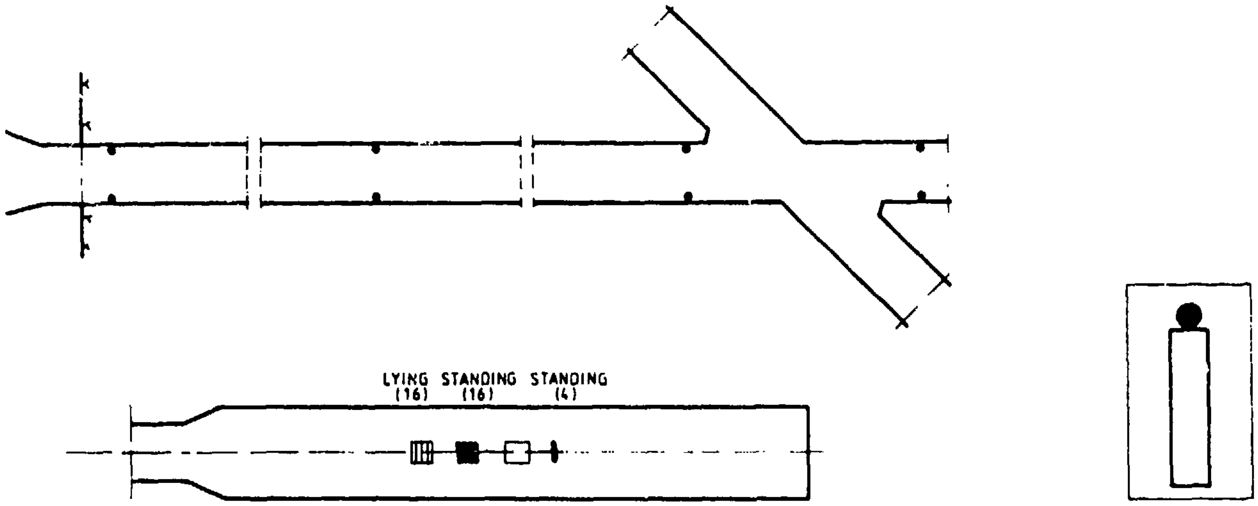

Figure 7. Artificial debris in test 3 and 4.

6. RESULTS

The overpressure at the entrance of the tunnel, which is used for calculating the blast outside the tunnel according to chapter 3 was measured to

Test	Pressure (kPa)
1	23
2	25
3	850
4	700.

The measured pressure outside along the tunnel axis are shown in figure 8 together with the calculated values according to /3/ and /4/. The measured values differ slightly from the calculated values according to /3/ and /4/ which, as is to be expected, gives conservative estimates. As the testing range was not made to be ideal for blast propagation studies a detailed comparison of precalculations based on ideal conditions with the actual measurements are not justified. This is especially true for measurements in other directions than the tunnel axis.

As the length of the crosstunnels in the installation is small their influence on the blast pressure outside the tunnel will be minor, /9/.

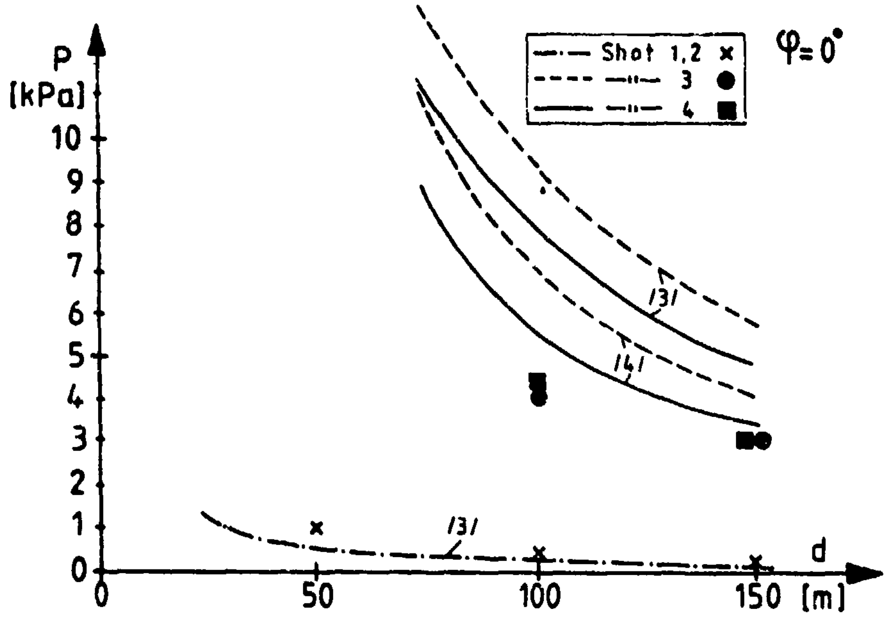

Figure 8. Measured overpressure outside the tunnel entrance

At the tests the blast was followed by debris at high velocity and then large amounts of black smoke came out of the entrance to the installation.

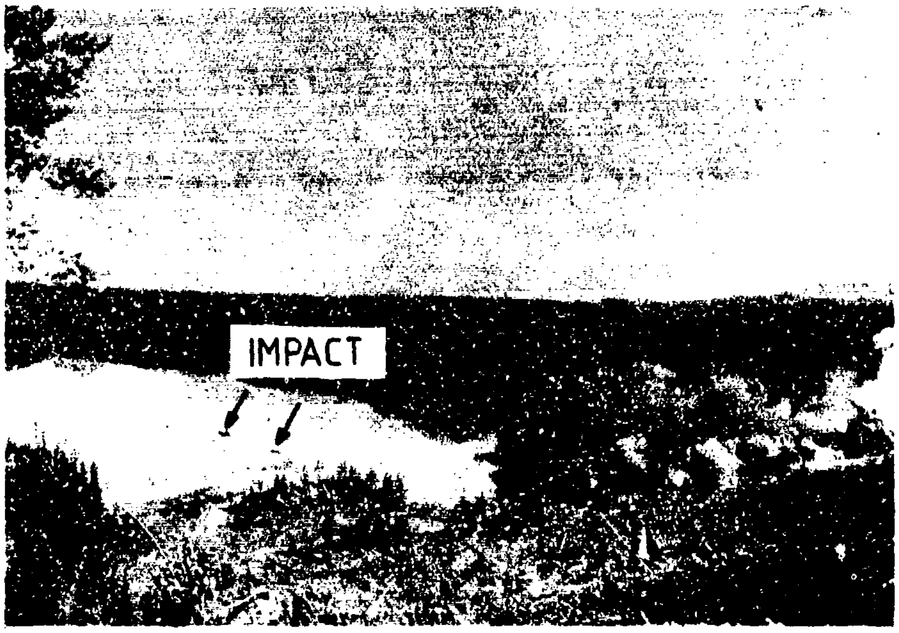

Figure 9. Fragments impacting the debris trap and smoke coming out of the entrance.

The artificial debris were found in the tunnel system and in a sector less than ±10° from the tunnel axis.

The debris close to the charge in the inner end of the chamber were all found remaining in the chamber after the test - though deformed.

In shot 3 the artificial debris were impacting on the chamber and tunnel walls and some of them stopped. Other went out of the tunnel. Most of the artificial cylinder shaped debris were recovered and identified. The velocities of the debris were measured from high-speed films. The maximum velocity measured was 120 m/s appr. 100 m outside the tunnel.

Shot 4 showed the debris trap to be efficient. Almost all debris were found in the tunnel system after the test while the artificial debris placed in the tunnel were thrown out. All debris were recovered and identified.

The debris trap would have been ever more effective if it had been wider.

The maximum debris velocity at shot 4 was measured to 135 m/s.

According to the precalculated values debris with velocities up to 150 m/s at the tunnel entrance are to be expected. For large debris like the artificial ones used in the test the air resistance does not lower the velocity very quickly in this range, /10/.

In figure 10 the location of debris after the tests 3 and 4 are shown.

7. CONCLUSIONS

The installation at ArtSS has shown to be a versatile tool for the measuring of the debris throw out of ammunition storage in rock. The tests performed so far have shown that the debris will fall in a narrow sector from the tunnel axis. The velocity of the debris is in correlation with precalculations.

8. ACKNOWLEDGEMENT

In the planning and during the execution of the tests many valuable suggestions have been given by different members of the Klotz-Club. Excellent efforts have also been made by a lot of individuals at ArtSS and FortF. The author is most thankful for all dedication and to outstanding achievements he has met during different stages of the project.

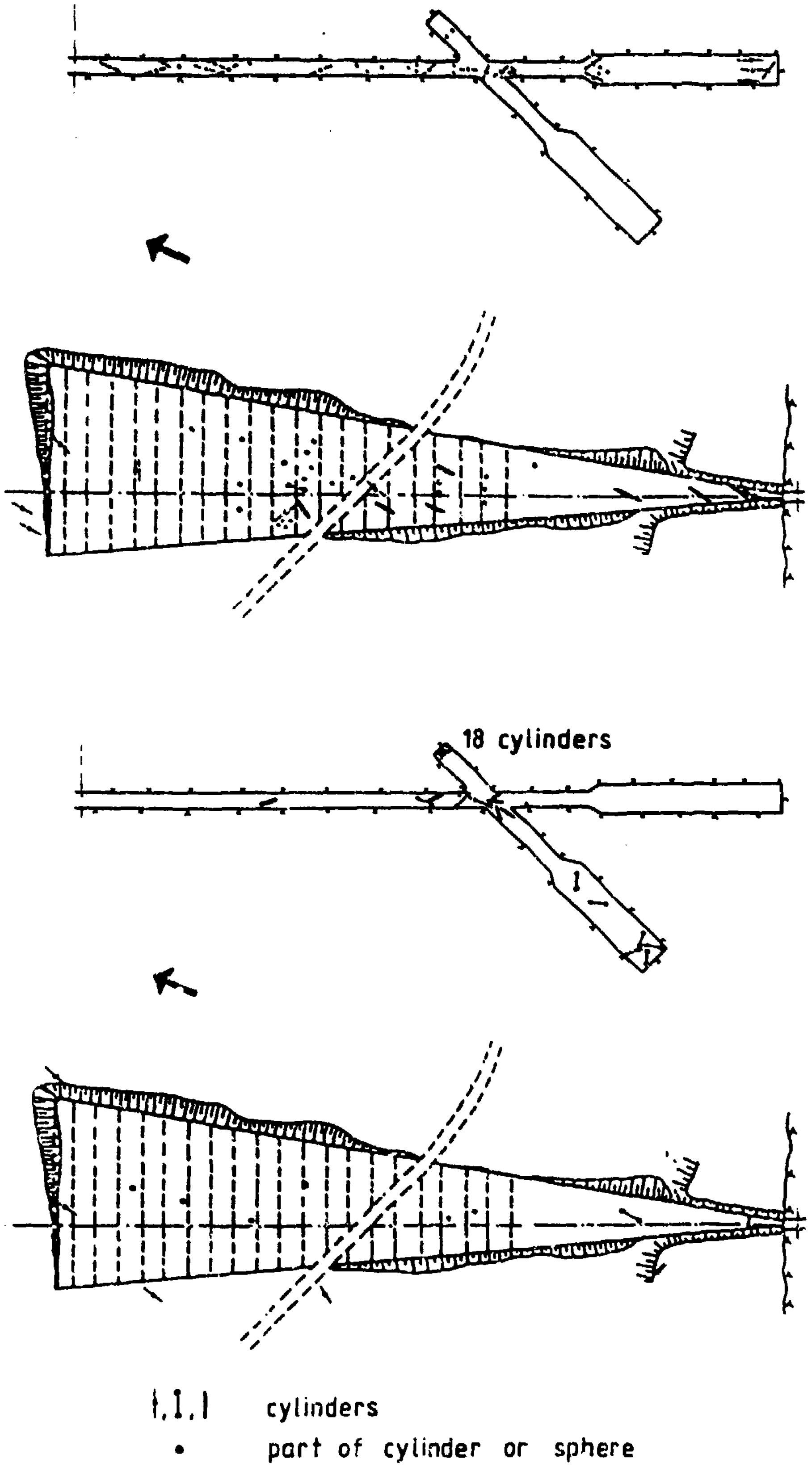

Figure 10. Debris postshot test 3 (above) and 4 (below).

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UNDERGROUND AMMUNITION STORAGE MAGAZINES

Blast Effects from Accidental Explosions

by

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presented at the

22nd Department of Defense Explosives Safety Seminar
Anaheim Marriott Hotel, Anaheim, California
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List of Symbols

A - Cross section area (m^2)

C_n - Constants

D - Equivalent tunnel entrance cross section diameter $(4A/\pi)^{0.5}$ (m)

D_c - Equivalent storage chamber cross section diameter $(4A/\pi)^{0.5}$ (m)

D_t - Equivalent tunnel cross section area $(4A/\pi)^{0.5}$ (m)

$\bar{d}_n$ - Inhabited Building Distance based on test results (m)

d_n - Inhabited Building Distance, Recommended (m)

K_n - Constant for angular attenuation

m, n, r - Exponents

P - Pressure at some distance outside an underground ammunition storage (bar)

P_a - Ambient pressure at sea level (bar)

P_o - Tunnel entrance pressure (bar)

Q - Explosive quantity (kg)

Q_T - Equivalent TNT explosive quantity (kg)

t - Duration of pressure wave (s)

V_c - Storage chamber volume (m^3)

V_T - Total volume of magazine (m^3)

W - Explosive energy (J)

a_o - Sound velocity in ambient air (m/s)

α - Angle from the centerline of the tunnel

γ - Ratio of specific heats, 1.4 for air

ρ_o - Ambient air density (kg/m^3)

CONTENTS

1. INTRODUCTION

Over the past 25 years, several experimental programs and studies have been undertaken to investigate the effects of accidental explosions in underground ammunition storage magazines.

Since 1973, a substantial part of this work has been coordinated through, and also performed by, the Klotz-Club (Ref. 1).

This work has covered most of the problems related to the quantity-distance determination (also denoted as Inhabited Building Distance) from blast waves originating from the tunnel exit. Also, investigations of required depth of rock-cover above an underground ammunition storage magazine have been performed ~~(Ref. 2).~~

Even so, the number and the extent that the various parameters may vary outside the limits of already established empirical equations are numerous.

So far, the most valuable result has been the verification of scale modeling techniques as a means of establishing Inhabited Building Distances, a fact reflected in the NATO Safety Principles AC/258 - D/258 Part III, which recommend that Inhabited Building Distances ~~be~~ determined by means of model testing for each specific underground storage site.

Cont'd pg. 84

Also, computer codes that can handle these problems have been developed, some based on empirical equations (e.g., INBLAST) and some utilizing theoretical physical equations (e.g., HULL and TUTTI). The INBLAST code is one dimensional, which limits its ability to handle problems that cannot easily be described in terms of volumes and vent areas (e.g., long tunnels). Nevertheless, it is a tool that can be used as a means of indicating an approximate value for the tunnel exit pressure. The INBLAST code is fast, easy, and inexpensive to run.

Computer codes like HULL and TUTTI can be very accurate, but they require highly specialized personnel and are relatively time-consuming and expensive. However, in most cases, these two codes are probably not as expensive as the extra land required, which becomes necessary if quantity-distance tables from national regulations are used.

All three computer codes described here have been used in a program to determine the quantity distances for a magazine concept very similar to the one presented in Reference 1 (the only difference being that the "Klotz" and the constrictions were deleted). The HULL code calculations on this concept are being presented in another paper at this seminar.

The results show fairly good agreement with 1/100-scale model tests of exactly the same geometry. So, for the future, with less expensive and faster computers, it seems likely that quantity distances will be established by means of computer modeling of each specific underground storage site. At present, however, the least expensive and fastest way to establish the quantity distances is by means of model tests.

The concept presented in Reference 1 (with its large single chamber) requires that mixing of compatibility groups be accepted to make it cost-effective.

In 1982, when a need arose for construction of new storage facilities in Norway, more extensive mixing of compatibility groups in a single chamber was accepted by the user nation than had previously been the case. This resulted in further development of the concept presented in Reference 1.

The only difference in the facilities actually constructed is the exclusion of the "Klotz" and the inclusion of a turnaround. The turnaround was included to allow trucks to unload in the expansion chamber without having to back out again. 1/100-scale model tests of this concept have been performed. Also, 1/100-scale model tests, where the expansion chamber and the turnaround were excluded, have been performed to verify the extra cost of the expansion chamber. In these later tests, the cross-sectional area of the exit tunnel was varied to investigate the possible effect of reducing the cross section.

The rest of this paper presents the methods by which these magazines and the explosives were modeled, an analysis of the results, and, finally, recommended Inhabited Building Distances for the various configurations.

2. TEST DESCRIPTION

2.1 Modeling Technique

The validity of scale model testing of underground ammunition storage magazines has been proved in previous test programs (Ref. 3 and 4).

A dimensional analysis of important parameters leads to the nondimensional relationship for distance versus pressure outside the tunnel entrance:

$$d/D = f(P/P_o,\ W/a_o^2\ \rho_o\ V, D\rho_o^{1/3}/W^{1/3},\ a_o t/D, \alpha) \qquad (1)$$

(See list of symbols for parameter definition.)

This relationship is used as a basis for the construction of models and in the analysis of results (Section 3).

Typical magazine layouts to be investigated at this time are shown in Figures 1 and 2.

The terrain in front of the tunnel entrance was modeled as a horizontal smooth surface so as not to introduce attenuation of the blast wave, which may not be present at the full-scale sites--a conservative, or safe, approach.

The magazines were modeled in steel in 1:100 scale (Figures 3 and 4.)

The storage chamber consisted of a detonation chamber with inside diameter of 106 mm and lengths varying from 677 to 1180 mm for the various desired volumes.

The tunnel sections were rectangular steel tubes with different cross-sectional areas.

For the magazine with an expansion chamber as a blast trap, a separate section was made in which the expansion chamber was a 420-mm-long tube with an inside diameter of 87.7 mm, giving an equivalent full-scale volume of 2540 m^3.

The turnaround was modeled by welding two 50- by 60-mm tubes to the expansion chamber, which was connected to the storage chamber by a 409-mm-long tunnel having an inside diameter of 63 mm. In this tunnel, two 50-mm-long constrictions with 45-mm diameters were modeled. The detonation (storage) chamber was vertically connected to the expansion chamber to simplify the loading of explosives. The justification for this solution is the fact that the blast wave must do a 90-degree turn in any case.

2.2 Instrumentation

The terrain model in front of and at the sides of the tunnel entrance was instrumented with six Celesco LC 33 pressure gages at distances shown in Figure 5. The tunnel sections were instrumented with Kistler 603 B pressure gages at locations shown in Figures 3 and 4.

2.3 Explosives

All explosives were Comp. A-3 in cylindrical 14.15-g pellets. Desired explosive quantities were made by taping the pellets to a rod. On some charges, a few grams of Comp.C-4 was added in order to get the exact desired quantity. All charges were initiated with a NONEL No. 3 detonator, which in turn was initiated by a No. 8 electrical detonator. The NONEL detonator had a 75-ms delay to separate the blast wave from the electrical detonator and the blast wave escaping from the tunnel entrance.

In the scaling and in the analysis of results, a TNT equivalency of 1.09 was used for the Comp. A-3 explosive.

2.4 Atmospheric Conditions

All results obtained during the test series and reported here have been scaled to ambient pressure at sea level (Pa [760 mmHg]).

3. RESULTS

3.1 Magazine with Expansion Chamber

The important model data for this configuation are summarized in Table 1, Figure 3, and Figure 5.

Figures 6, 7, and 8 are diagrams of the external pressure versus full-scale distance from the tunnel entrance for the three different geometries tested. In Figure 9, these results are scaled with tunnel diameter and tunnel entrance pressure.

The data reduction of tunnel entrance pressures showed relatively poor consistency of the peak pressure from test to test. Instead, the blast velocity was taken from the blast arrival times to measuring points MP 2 and MP 3 (see Figure 3). This blast velocity was then used to calculate the peak incident pressure close to the entrance with the ideal gas equation (2).

$$P_o/P_a = \frac{2\gamma}{\gamma + 1} (M^2 - 1) \qquad (2)$$

The tunnel entrance pressures found in this way show much better consistency.

Compared to previous tests with underground ammunition storage magazines, this configuration is very complex and special. It was therefore regarded as most correct to treat this configuration separately in the analysis of results leading to empirical equations giving tunnel entrance pressure and Inhabited Building Distance.

The following empirical relationship was found for the tunnel entrance pressure:

$$P_o = 5.6 \cdot (Q_T/V_T)^{0.54} \qquad (3)$$

Based on a reduced version of Eq. 1, the distance $\bar{d}_n$ to where the pressure is P was found to be:

$$\bar{d}_n/D = K_n \cdot 1.84 \cdot (P_o/P)^{0.70} \qquad (4)$$

Here, K_n is the factor for angular attenuation and is 1.0 for the 0° to 30° sector.

At 60°, K_n was found to be approximately 0.67. This fits well with previous results for the angular attenuation factor. Thus, the previous results for K_n will be the basis for Inhabited Building Distances for [illegible] different sectors (Section 4).

The reduction of Eq. 1, leading to Eq. 4, will be further discussed in Section 3.3.

3.2 Magazine with Straight Tunnel

The important model data for this configuration are summarized in Table 2 and Figures 4 and 5. Figures 10 through 15 are diagrams of the external pressure versus full-scale distance from the tunnel entrance for six of the geometries tested. In Figure 16, these results are scaled with tunnel entrance pressure and diameter.

As for the magazine with expansion chambers, poor consistency in tunnel entrance pressures was observed for this concept, too. The same procedure for the definition of P_o, as described in Section 3.1, was then used for this concept as well, resulting in the following relationship for the tunnel entrance pressure:

$$P_o = 16.4 \cdot (Q_T/V_T)^{0.54} \cdot (D_t/D_c)^{0.24} \qquad (5)$$

The relationship for the distance $\bar{d}_n$ to where the pressure is P, using the reduced version of Eq. 1, was found to be:

$$\bar{d}_n/D = K_n \cdot 0.77 \cdot (P_o/P)^{0.77} \qquad (6)$$

As for Eq. 4, K_n is equal to 1.0 for the 0° to 30° sector. At 60°, K_n is 0,74 (see Figure 16). This is higher than 2/3 but close enough to indicate that the angular attenuation previously found is valid.

Recommended Inhabited Building Distances for different sectors for this configuation are presented in Section 4. Section 3.3 contains a more detailed discussion of the results.

3.3 Discussion of Results

As mentioned in Section 2, the relationship of pressure attenuation to distance outside an underground ammunition storage magazine generally is described by Eq. 1:

$$d/D = f(P/P_o,\ W/a_o^2 \rho_o V, D\rho_o^{1/3}/W^{1/3},\ a_o t/D,\ \alpha)$$

For practical purposes, this equation is too complex, and many underground ammunition magazines often have geometrical variations that cannot be covered in a single equation.

This leads to the conclusion that for each concept of magazine layout, a separate set of equations should be determined. As a result, some of the dimensionless terms in Eq. 1 can be singled out:

- All the different tests with underground ammunition storage magazines show that the distance to where the pressure is P strongly depends on the tunnel entrance diameter and on the tunnel entrance pressure. The tunnel diameter and the term P/P_o are therefore essential for the definition of safe ranges outside a specific magazine.

- The term $a_o t/D$ describes the duration of the blast wave escaping from the tunnel entrance. Unpublished analyses of the influence of the duration (or impulse) of the escaping blast wave on the safe range indicate an exponent on the duration equal to 0.15 ± 0.02. This means that for a specific magazine concept, where the stored explosives quantity varies within a factor of perhaps 2 to 3, the impact on the safe range will be the explosive quantity to a power of approximately one-third times 0.15. Within a factor of 3 on the explosives quantity, this means that the error on the calculated safe range will be not more than 6% $({}_3 0.33 \cdot 0.15)$ and for practical purposes can be ignored.
- The nondimensional loading density, $W/a_o^2 \rho_o V$, in Eq. 1 is a function necessary to describe the tunnel entrance pressure P_o. Since P_o will be used in the reduced version of Eq. 1, this term will be used instead to define P_o in a separate equation.
- The term $D\rho_o^{1/3}/W^{1/3}$ is the scaled diameter of the tunnel entrance relative to the amount of energy passing through. This is a term that, for each specific magazine concept, is taken care of by some constant or related to the size of the storage chamber in the definition of P_o.
- To describe the angular attenuation of the escaping pressure wave, the angle α was chosen to represent different sectors, where each sector is given an empirically determined attenuation factor in the final equation.

Eq. 1 thus reduces to:

$$d/D = f_1(P/P_o)\, f_2(W/a_o^2 \rho_o V, D\rho_o^{1/3}/W^{1/3}, a_o t/D)\, f_3(\alpha) \qquad (7)$$

where f_2 (.......) reduces to a constant C_1 for each specific magazine and f_3 (α) reduces to the constant K_n. Empirically, it has been found that f_1 (P/P_o) is best represented as a power curve within the limits of d/D of practical interest; thus:

$$d/D = C_1(P_o/P)^n \tag{8}$$

The exponent n has been defined for a large number of different tests, ranging from shock tubes to underground ammunition magazines and blast leakage into rooms. Preliminary analysis of such data indicates that n typically varies between 0.67 and 0.9, with most of the results between 0.7 and 0.8. Another observation is that n tends to increase for decreasing pressure P, which also can be observed in the lower region of pressures for an unconfined charge. Indications were also found that n increases with decreasing duration on the escaping blast wave P_o.

Since these factors for different magazine concepts are mixed, it is natural that n will change from concept to concept.

The constant, C_1, will naturally vary considerably, but mostly as a result of varying exponent n, since the range of P_o/P of interest usually is on the order of 500 to 5000.

In Sections 3.1 and 3.2, Eq. 8 is given for the two magazine concepts described in this report (Eq. 4 and 6).

The tunnel entrance pressure P_o is, as described, a function of the scaled loading density and the tunnel diameter and can be written in the form:

$$P_o = C_2 \, (Q_T/V_T)^m \, (D_t/D_c)^r \tag{9}$$

For simplicity, the explosive energy W is replaced by the equivalent TNT charge weight Q_T, the storage chamber volume by the total volume, and the scaled tunnel diameter by the ratio between tunnel diameter and storage chamber diameter.

In Section 3.2, Eq. 9 is given for the magazine concept without expansion chamber (Eq. 5).

In Section 3.1, Eq. 9 is given for the magazine concept with expansion chamber (Eq. 3). As can be seen, Eq. 3 is in an even more reduced form than Eq. 5. This is a result of the complexity of this magazine concept, which means that the geometrical ratio D_t/D_c is not sufficient to represent the variations in layout possible in this configuation. Instead of just D_t/D_c, one would need factors describing size of expansion chamber, length of tunnel between storage chamber and expansion chamber, number and sizes of constrictions, and length and angle of turnaround tunnel. It was not within the scope of this test series to investigate the influence of variation of these parameters; thus, all geometrical parameters were put into a single constant except for the total volume--meaning variation in storage chamber volume and to a certain extent in tunnel length. Eq. 3 is therefore valid for a magazine with layout as shown in Figures 1 and 3, with possible variations in storage chamber volume, explosive quantity, and tunnel length.

The results for the tunnel entrance pressure P_o are, as described in Sections 3.1 and 3.2, obtained from the blast wave velocity close to the entrance. This was done to obtain pressures that were consistent from test to test and not influenced by reflections inside the magazine.

Typical recordings from the pressure transducers in the tunnel showed a large number of reflections with increasing magnitude over time and often with a "plateau" between them. Thus, P_o represents the first peak pressure arriving at the tunnel entrance and was judged to be the "driving" force for the peak of the blast wave at distance d outside the magazine. This finding is based on a close examination of the pressure-time histories recorded outside the magazine compared to those recorded at the tunnel entrance.

Reflections of pressure higher than P_o, recorded at the tunnel entrance, could easily be retrieved from the pressure-time history recordings taken from measuring points outside. This means that the reflections did not coalesce with the first peak, which would have resulted in enhancement of the peak pressure outside. These observations are valid at least out to ranges where the pressure is decreased to less than 50 mbar.

4. RECOMMENDED INHABITED BUILDING DISTANCES

The Inhabited Building Distance outside an underground ammunition storage magazine is defined as the distance from the tunnel entrance to where the pressure is 50 mbar. (AC/258-D/258 and TFF 738, Norwegian national regulations).

The equations presented for $\bar{d}_n$ represent curve fits for data obtained from tests (50% confidence level) and should not be used directly for the determinaton of Inhabited Building Distances, since they do not include any safety factors (except for a safety factor resulting from the fact that the models have smooth tunnel walls, while most real magazines have more or less rough tunnel walls). AC/258-D/258, Part III, Section IV, para 235, does not give any recommendations for the data reduction process or evaluation of results obtained from model tests, but D/258 Part I requires a 90% confidence level.

Reference 5 recommends using test results (90% confidence level) with a 20% increase to account for the small scale used. TFF 738 also requires adding 20% to the 50-mbar distance as a safety factor. Since the number of test results is too limited to establish a 90% confidence level, it was instead recommended to assume that a 10% increase to the curve fits (50% confidence level) is equivalent to a 90% confidence level.

Thus, recommended Inhabited Building Inhabited Distances d_n are the distances found with the equations for $\bar{d}_n$ times 1.1 times 1.2 = 1.32.

Equations 3 through 6 define the pressure attenuation outside two different underground magazine concepts. Inhabited Building Distance equations for these concepts are thus defined, using P = 50 mbar and the following factors for angular attenuation K_n:

Angle	Equation
0° to 30°	$K_n = 1.0$
30° to 60°	$K_n = 0.89$
60° to 90°	$K_n = 0.67$
90° to 120°	$K_n = 0.5$
120° to 180°	$K_n = 0.25$

The chart below summarizes the necessary equations to define Inhabited Building Distances:

Magazine type	Magazine without expansion chamber	Magazine with expansion chamber
Test result 50 mbar Distance, $\bar{d}_n$ (m)	$\bar{d}_5 = 7.7 \cdot D \cdot P_o^{0.77}$	$\bar{d}_5 = 15.0 \cdot D \cdot P_o^{0.70}$
	$\bar{d}_4 = 6.9 \cdot D \cdot P_o^{0.77}$	$\bar{d}_4 = 13.3 \cdot D \cdot P_o^{0.70}$
	$\bar{d}_3 = 5.2 \cdot D \cdot P_o^{0.77}$	$\bar{d}_3 = 10.0 \cdot D \cdot P_o^{0.70}$
	$\bar{d}_2 = 3.9 \cdot D \cdot P_o^{0.77}$	$\bar{d}_3 = 7.5 \cdot D \cdot P_o^{0.70}$
	$\bar{d}_1 = 1.9 \cdot D \cdot P_o^{0.77}$	$\bar{d}_1 = 3.8 \cdot D \cdot P_o^{0.70}$
Tunnel entrance pressure, P_o (bar)	$P_o = 16.4 \cdot (Q_T/V_T)^{0.54} \cdot D_t/D_c)^{0.24}$	$P_o = 5.6 \cdot (Q_T/V_T)^{0.54}$
Recommended Inhibited Building Distance, d_n (m)	$d_n = 1.32 \cdot \bar{d}_n$	

These equations are valid for the following:

Explosives quantity: $150.000 \text{ kg} < Q_T < 450.000 \text{ kg}$

Loading density: $15 < Q_T / V_T < 50$

In Figure 17, a comparison of the 50-mbar distances, $\tilde{d}_n$ for the 0° to 30° sector for the two magazine concepts, is presented.

5. CONCLUSIONS

Model tests for the two different concepts were successfully performed, resulting in determination of relationships for the definition of Inhabited Building Distances for the two magazine concepts tested.

Cont'd

The test series clearly demonstrated the need to perform model tests when magazine concepts differ from previously tested magazine concepts.

The tests also demonstrated the advantage of the expansion chamber as a means of reducing the Inhabited Building Distance. For a typical situation with an explosive quantity of 300,000 kg, the area within the Inhabited Building Distance increases by almost 130% when the expansion chamber is deleted.

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Table 1. Data for the 1:100 steel model of magazine with expansion chamber. (See Figure 3 for further details of measurements.)

Test no Sizes	27 - 29	30	31
Storage chamber volume, V (dm3)	8.65	5.97	5.97
Expansion chamber volume (dm3)	2.54	2.54	2.54
Total volume of magazine, V_T (dm3)	17.10	14.42	14.43
Tunnel entrance cross section, h x b (mmxmm)	40x40	40x40	50x60
Equivalent tunnel entrance diameter, D (mm)	45.1	45.1	61.8
Charge weight, Q (g comp. A-3)	285	228	228
Equivalent TNT-charge weight, Q_T (g)	311	249	249
Q_T/V (kg/m3)	35.91	41.63	41.63
Q_T/V_T (kg/m3)	18.17	17.23	17.22

Table 2. Data for the 1:100 steel model of magazine without expansion chamber. (See Figure 4 for further details of measurements).

Test no Sizes	32	34	36	37	38	39
Storage chamber volume, V (dm3)	10.41	10.41	10.41	10.41	10.41	10.41
Tunnel volume, V_t (dm3)	4.15	2.21	1.08	1.08	0.55	4.15
Total volume of magazine V_T (dm3)	14.56	12.62	11.49	11.49	10.96	14.56
Tunnel cross section h x b (mm x mm)	50x60	40x40	28x28	28x28	20x20	50x60
Equivalent tunnel diameter, D_t (mm)	61.8	45.1	31.6	31.6	22.6	61.8
Storage chamber diameter Dc (mm)	106	106	106	106	106	106
D_t/Dc	0.583	0.425	0.298	0.298	0.213	0.583
Charge weight, Q (g Comp. A-3)	193	193	193	389	193	389
Equivalent TNT-charge wieght, Q_T (g)	210	210	210	424	210	424
Q_T/V (kg/m3)	20.17	20.17	20.17	40.73	20.17	40.73
Q_T/V_T (kg/m3)	14.42	16.64	18.26	36.87	19.14	29.12

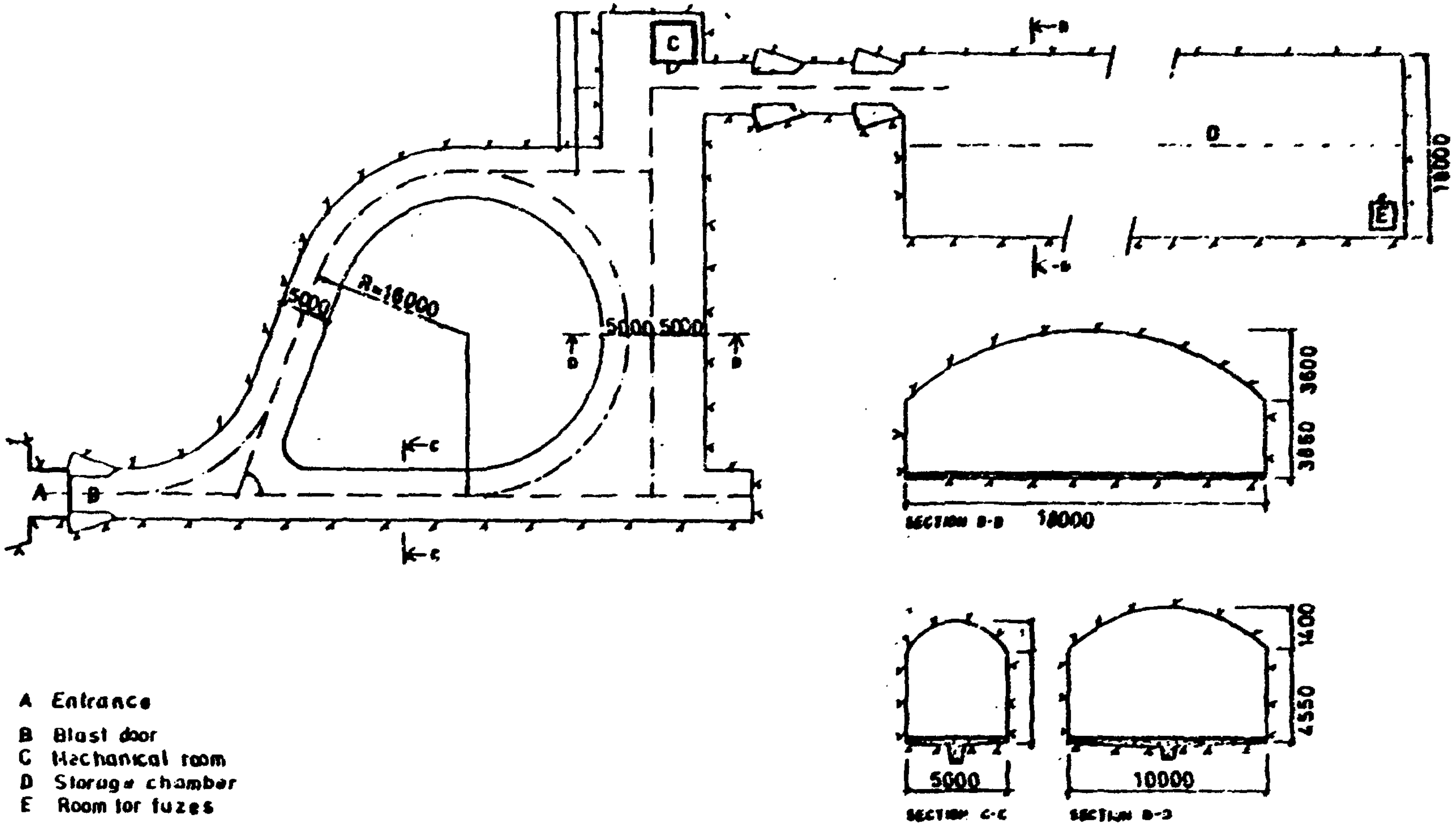

Figure 1. Typical magazine with 2500-m^3 expansion chamber as blast trap.

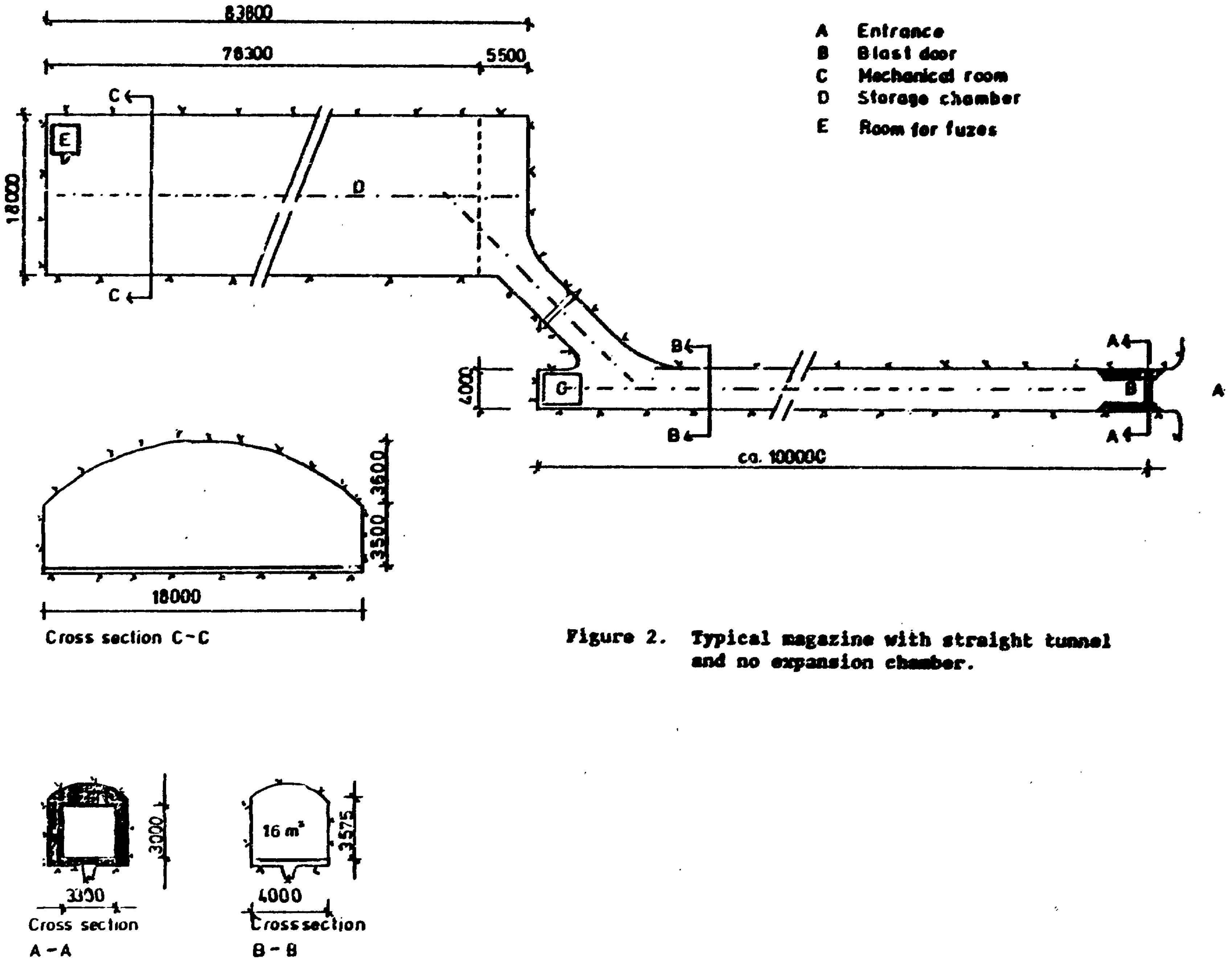

Figure 2. Typical magazine with straight tunnel and no expansion chamber.

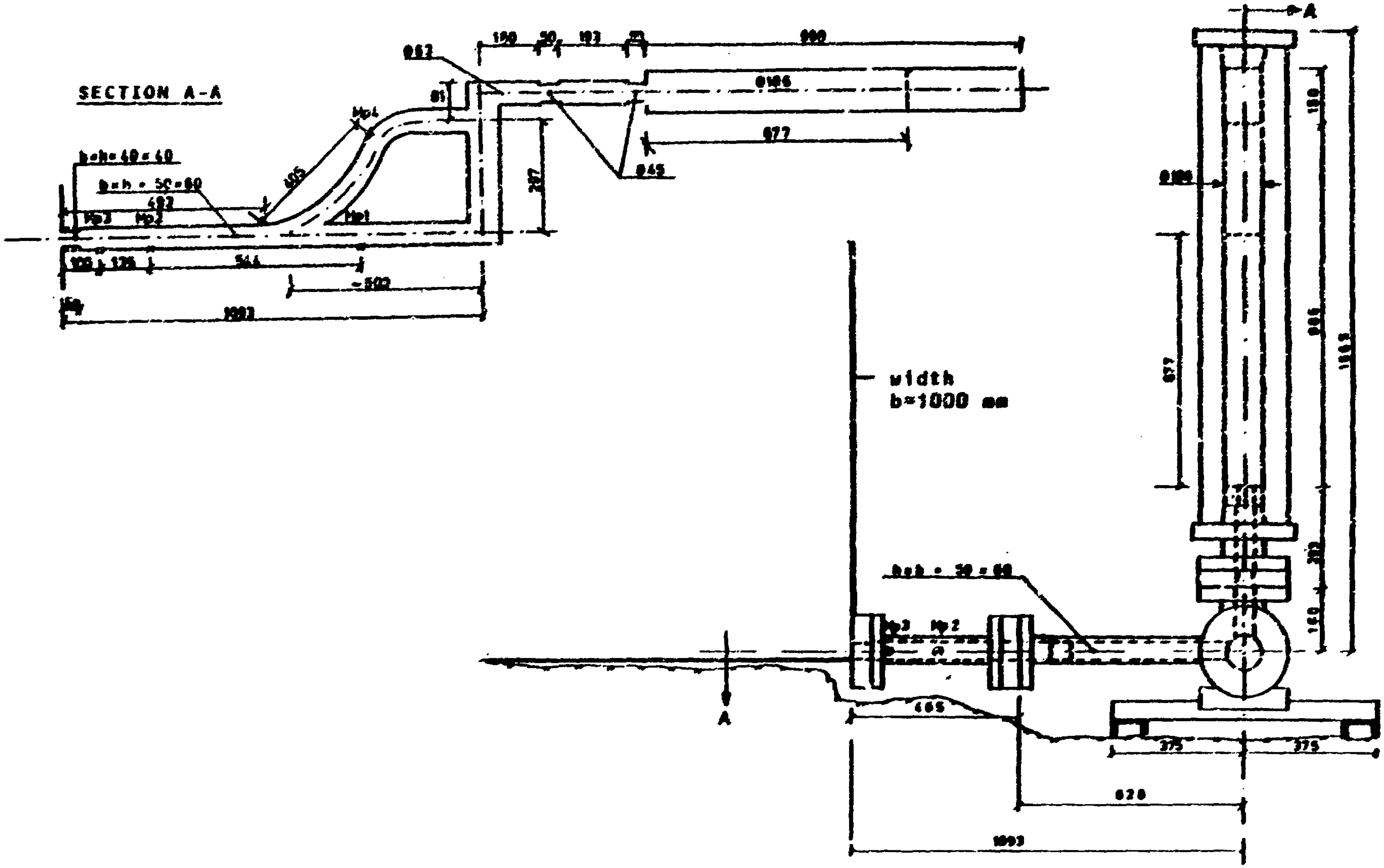

Figure 3. 1:100 steel model of ammunition storage magazine with expansion chamber.

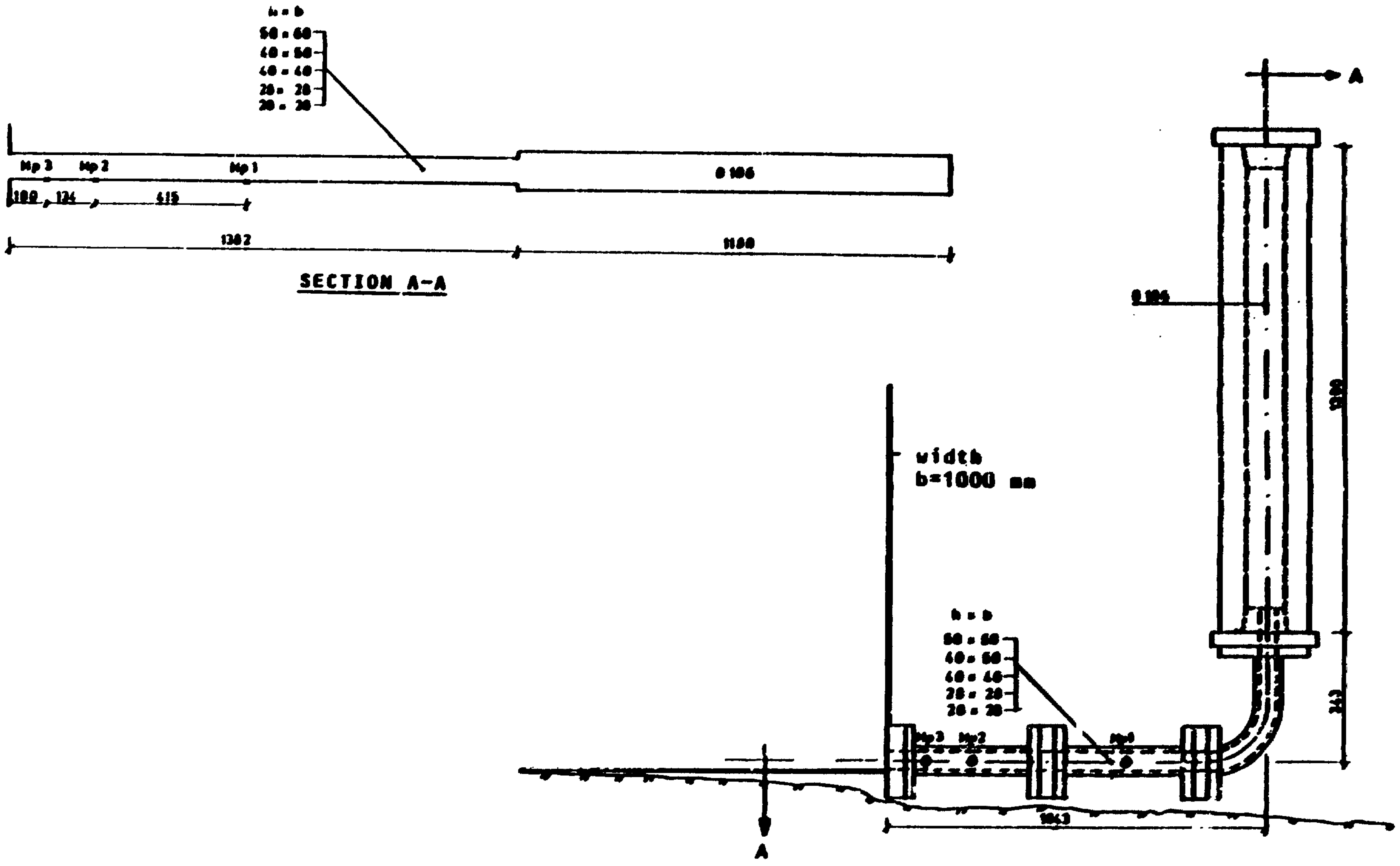

Figure 4. 1:100 steel model of ammunition storage magazine with straight tunnel.

SHOT	27-28	29-39
r6	0.99 m	1.51 m
r7	4.05 m	5.0 m
r8	8.04 m	9.87 m
r10	1.0 m	1.02 m
r11	2.95 m	4.01 m
r12	6.02 m	8.01 m

Distance to measuring points

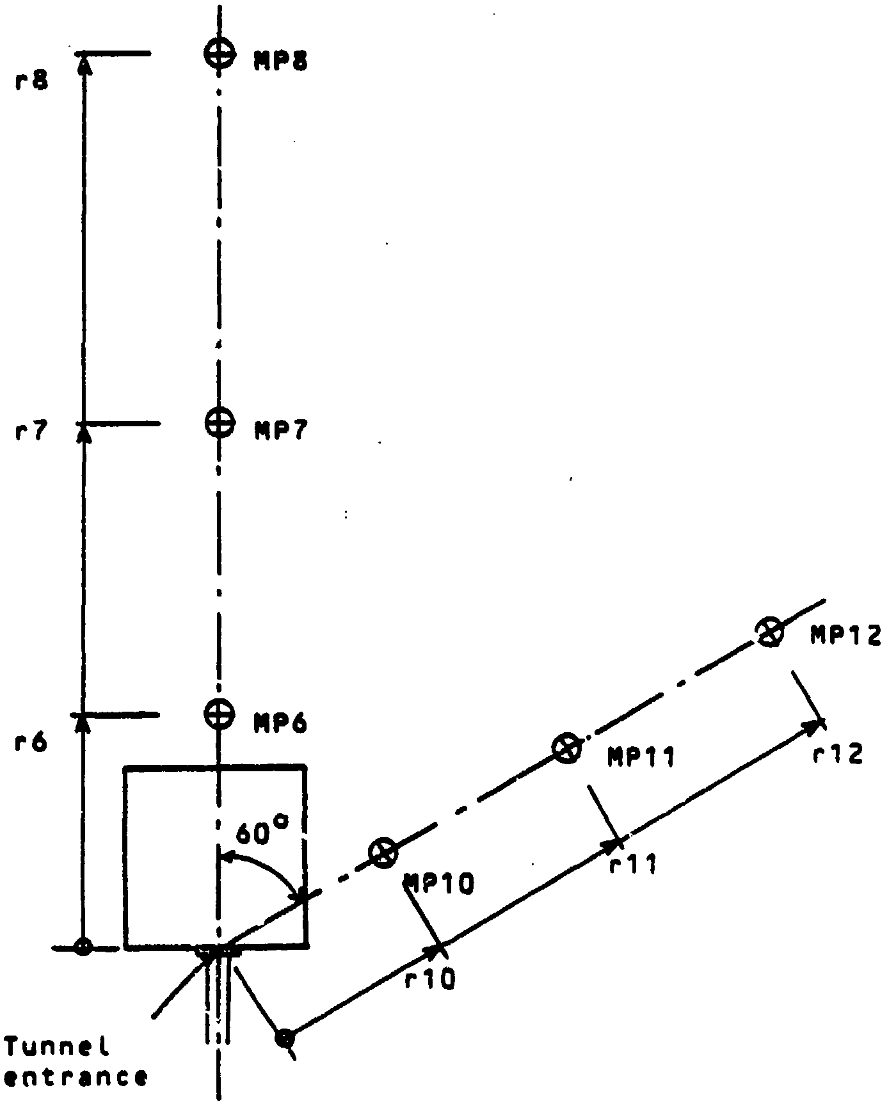

Figure 5. Plan view of measuring points outside tunnel entrance.

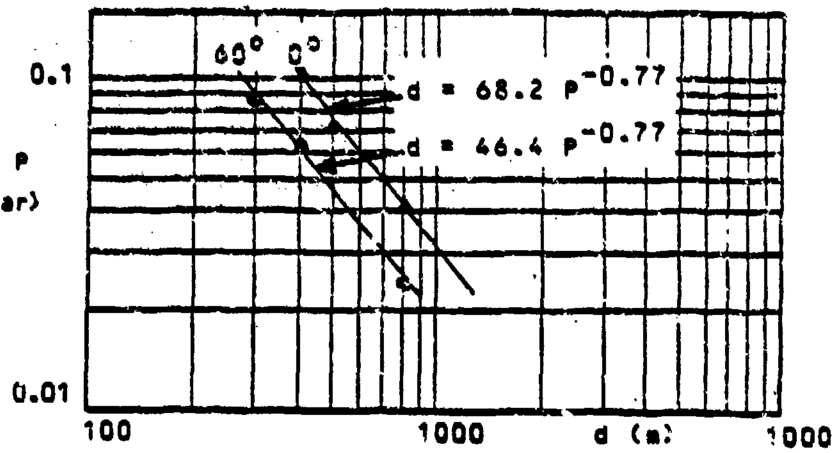

Figure 6. Magazine with 8650-m^3 storage chamber and 2540-m^3 expansion chamber, 16-m^2 constriction at entrance. Q = 311,000 kg.

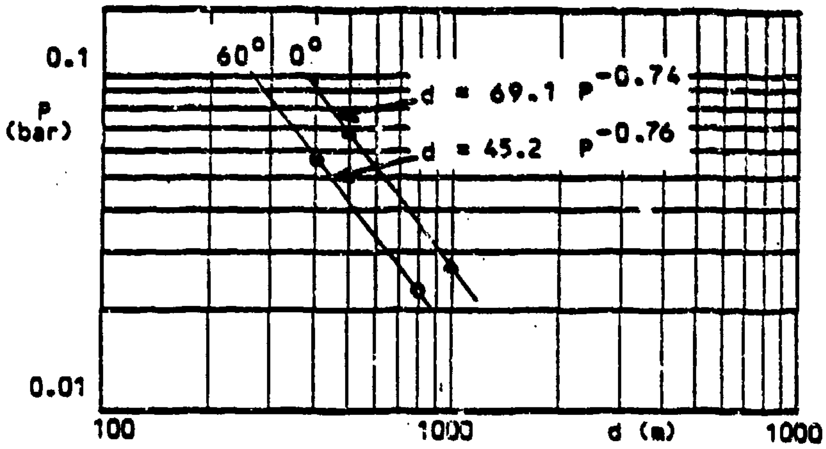

Figure 7. Magazine with 5970-m^3 storage chamber and 2540-m^3 expansion chamber, 16-m^2 constriction at entrance, Q = 249,000 kg.

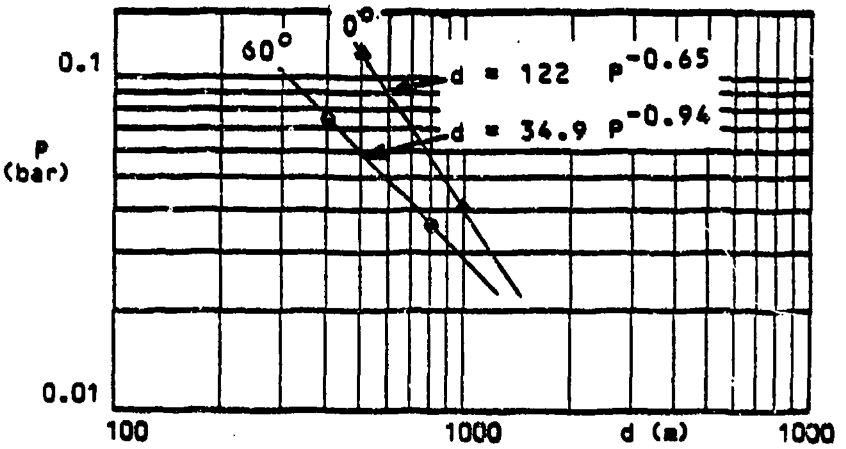

Figure 8. Magazine with 5970-m^3 storage chamber and 2540-m^3 expansion chamber, 30-m^2 entrance cross section area, no constriction, Q = 249,000 kg.

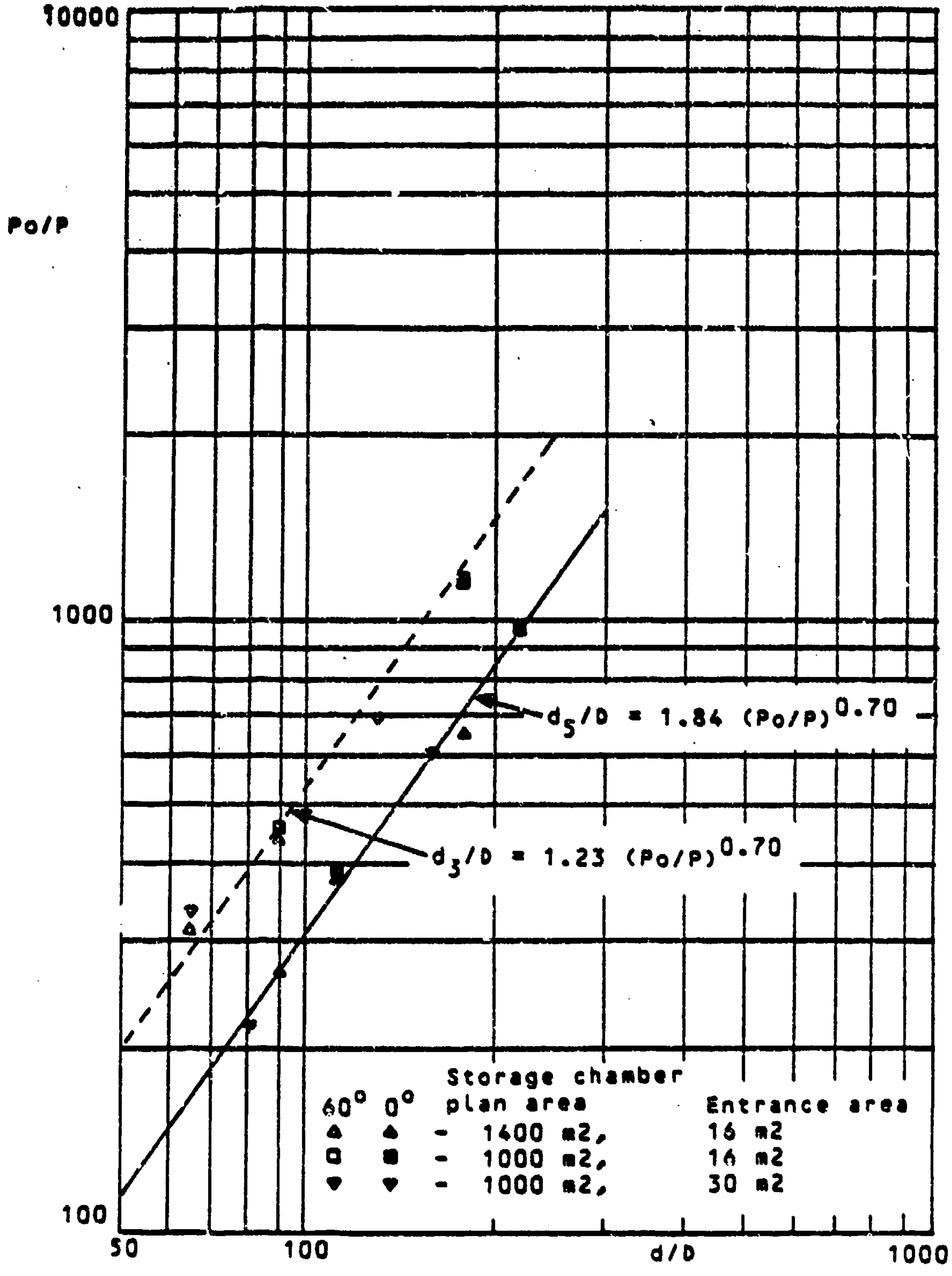

Figure 9. Magazine with expansion chamber, scaled distance versus scaled pressure.

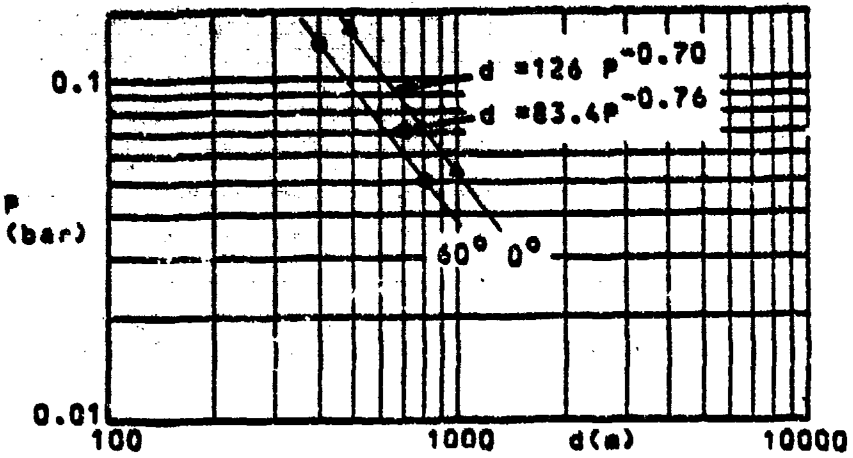

Figure 10. Magazine with 10,410-m^3 storage chamber and no expansion chamber. Tunnel cross section area = 30 m^2. Q = 210,000 kg.

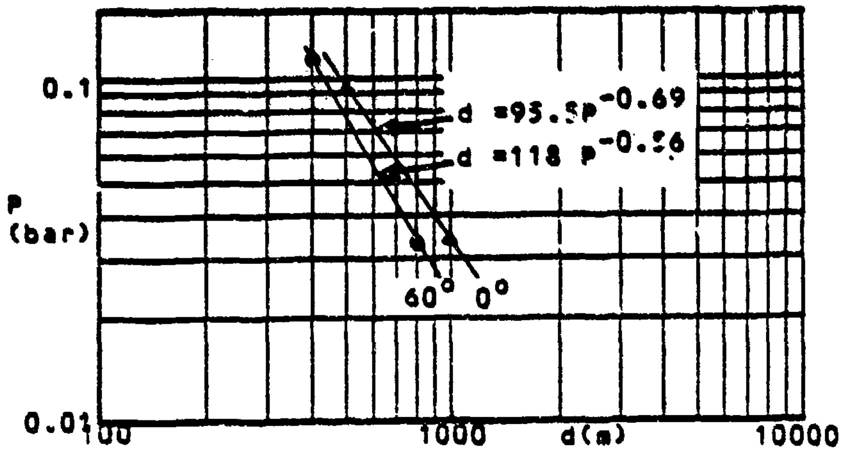

Figure 11. Magazine with 10,410-m^3 storage chamber and no expansion chamber. Tunnel cross section area = 16 m^2. Q = 210,000 kg.

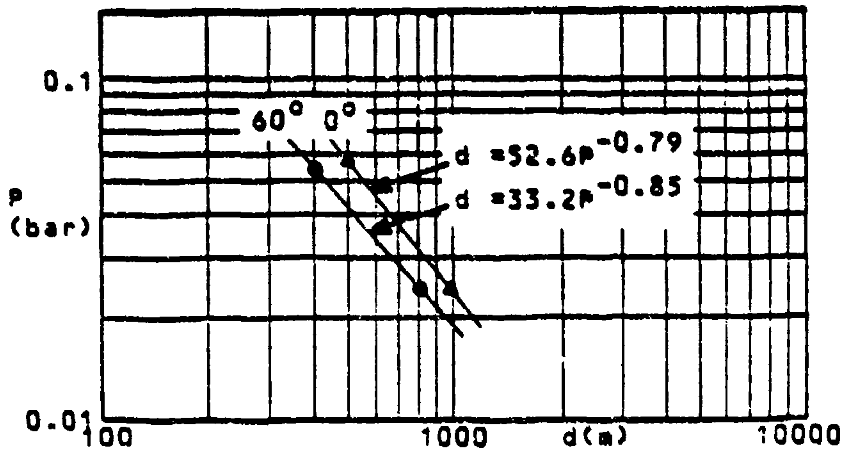

Figure 12. Magazine with 10,410-m^3 storage chamber and no expansion chamber. Tunnel cross section area = 8 m^2. Q = 210,000 kg.

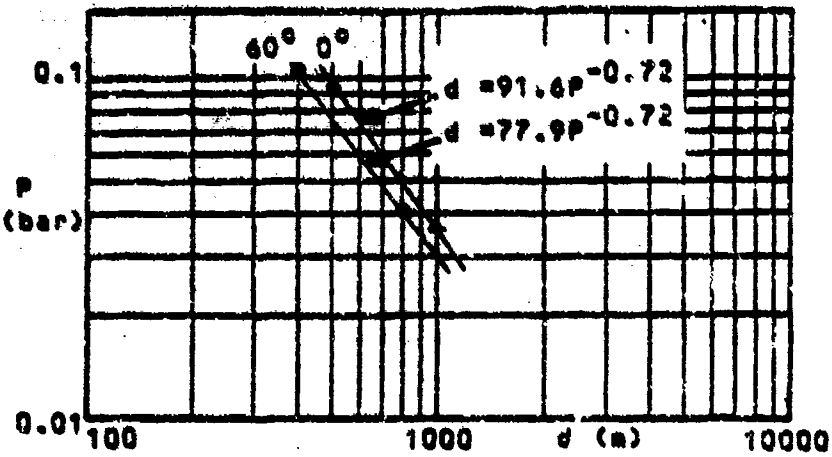

Figure 13. Magazine with 10,410-m^3 storage chamber and no expansion chamber. Tunnel cross section area = 8 m^2. Q = 424,000 kg.

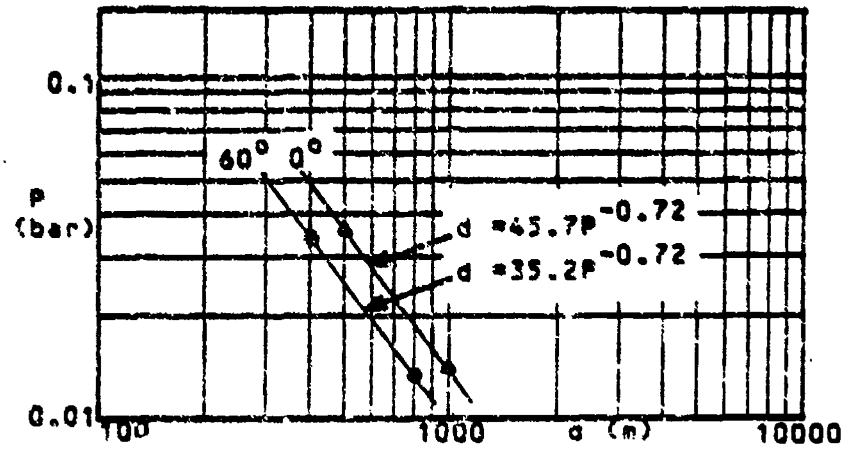

Figure 14. Magazine with 10,410-m^3 storage chamber and no expansion chamber. Tunnel cross section area = 4 m^2. Q = 210,000 kg.

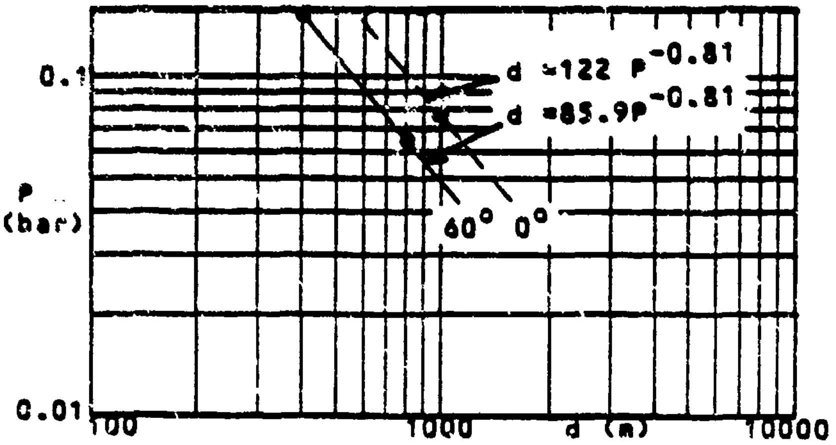

Figure 15. Magazine with 10,410-m^3 storage chamber and no expansion chamber. Tunnel cross section area = 30 m^2. Q = 424,000 kg.

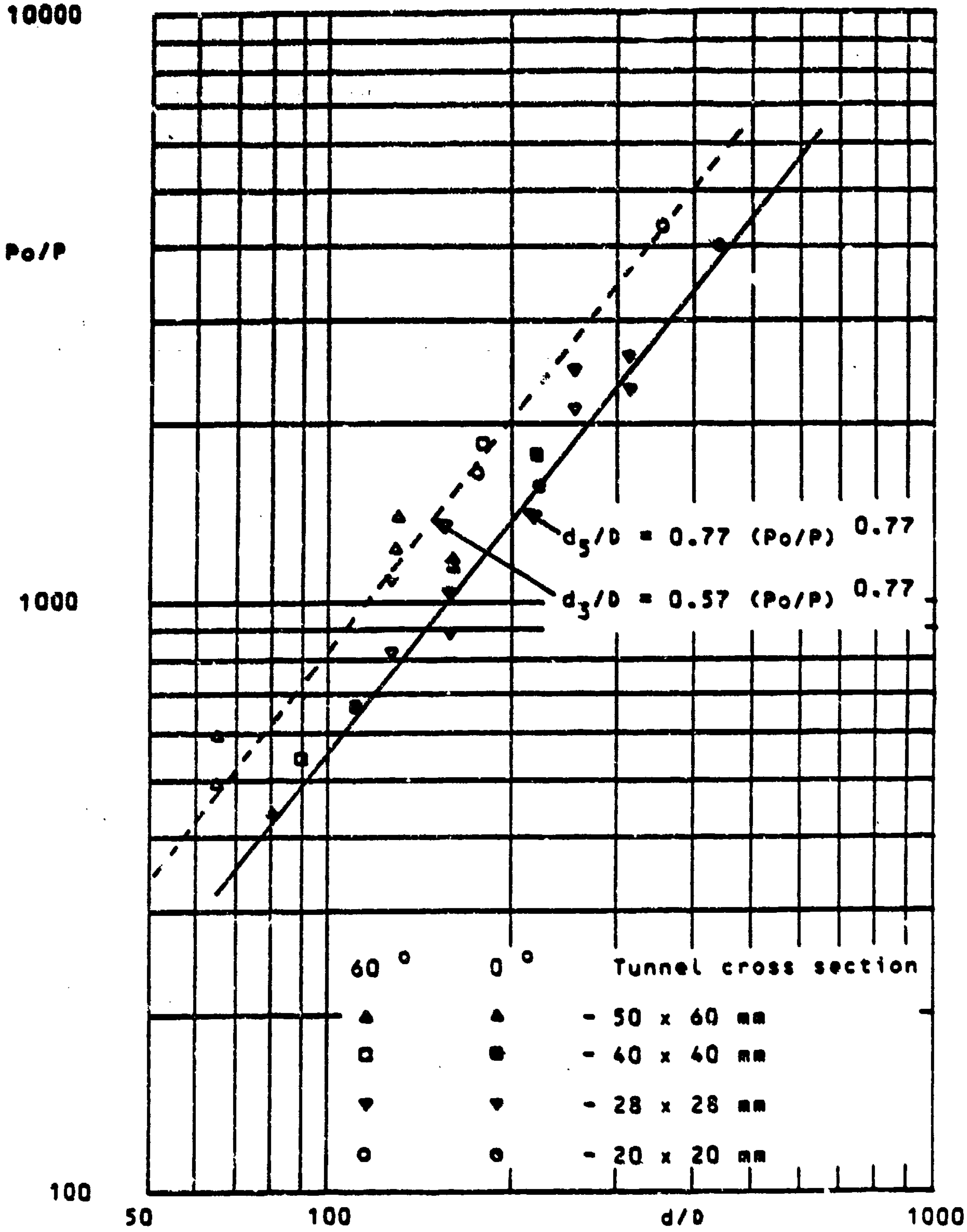

Figure 16. Magazine without expansion chamber, scaled distance versus scaled pressure.

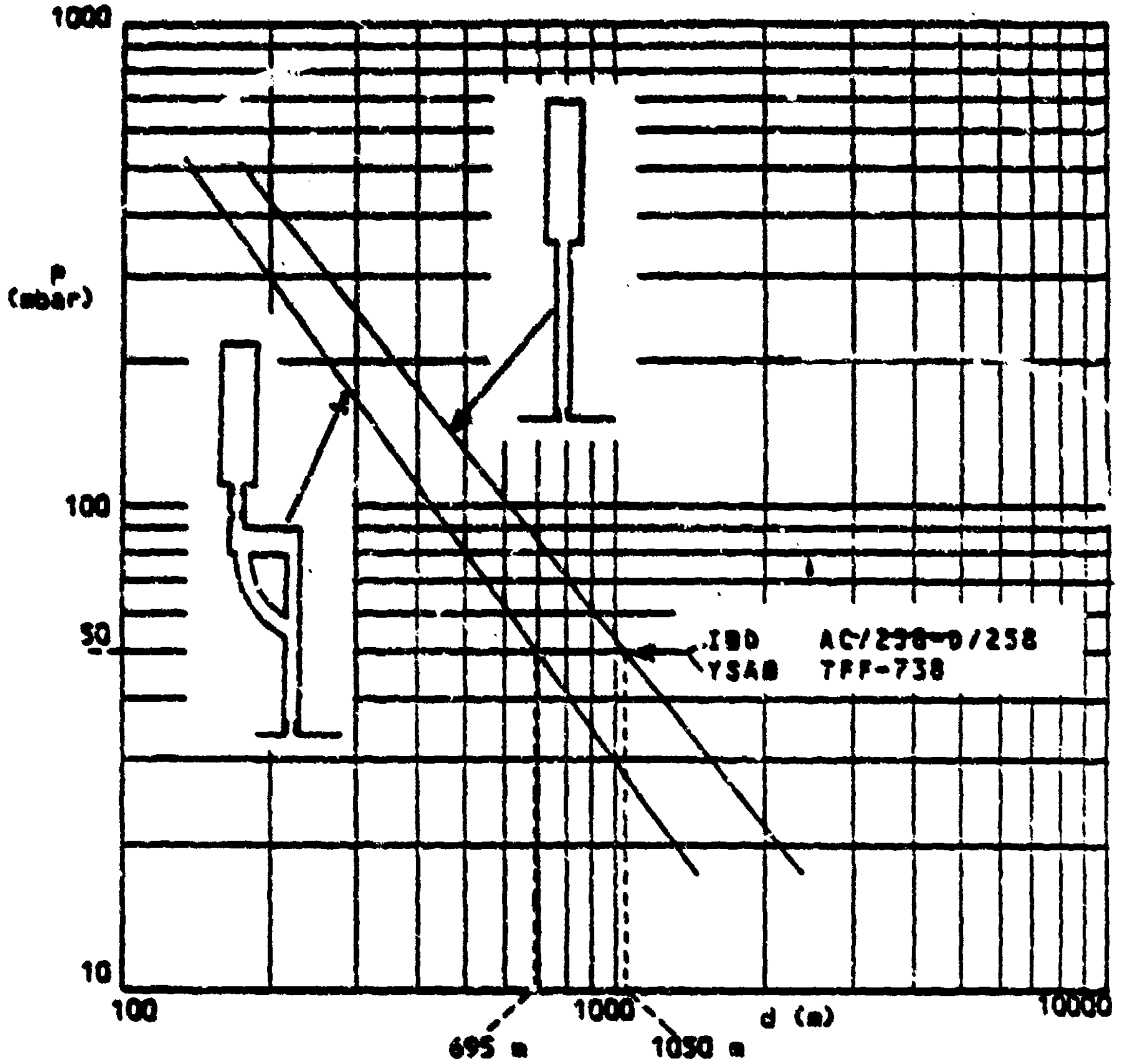

Figure 17. Underground ammunition storage. Comparison of distance versus pressure with and without expansion chamber. Storage chamber volume = 8000 m^3. Expansion chamber volume = 2540 m^3. NEQ = 300,000 kg. Tunnel length = 100-m, 0° to 30° sector. Safety factors not included.

CALCULATION OF AIRBLAST FROM UNDERGROUND AMMUNITION STORAGE MAGAZINES*

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I. INTRODUCTION

The storage of munitions in underground facilities provides a potential hazard to surrounding buildings or populations. Current placement of such facilities relative to above-ground structures is based on long standing curves and scaling relations for the peak airblast overpressure as a function of weight of explosives and distance and angle relative to the tunnel opening. The suggested scaling relation for a 50 mbar safety criterion is Shown.

$$d = D \cdot F \cdot P_o^{0.67}$$

where d is the distance to 50 mbar (m)
D is the main tunnel diameter (m)
P_o is the gas pressure in the main passageway (bars)
and F is a tabulated directional factor.

This relationship is based on a variety of explosive weight-to-volume ratios. However, recent storage designs call for larger amounts of explosives and lower explosive storage densities than were considered in developing the relationship. It has not been demonstrated that the same relation holds for these new conditions. In addition, the high cost of real estate

Cont'd

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*This work was sponsored by the Norwegian Defence Construction Service (NDCS), Oslo, Norway, and the Department of Defense Explosives Safety Board, Alexandria, Virginia.

suggests that small changes in the safe distances will have a significant financial impact on the storage of munitions.

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A coordinated program of experiments and calculations is being conducted by the Norwegian Defence Construction Service (NDCS) to reduce the uncertainties in determination of safe distances and to define the angular distribution of overpressure. As a part of this program, S-CUBED provided hydrodynamic flow calculations of the detonation, internal propagation and external expansion of blast waves in a two-dimensional model designed to simulate the NDCS experiment, "Test 1". The scaled test model is shown in Figure 1.

Figure 1. Photograph of the NDCS Scaled Test Model.

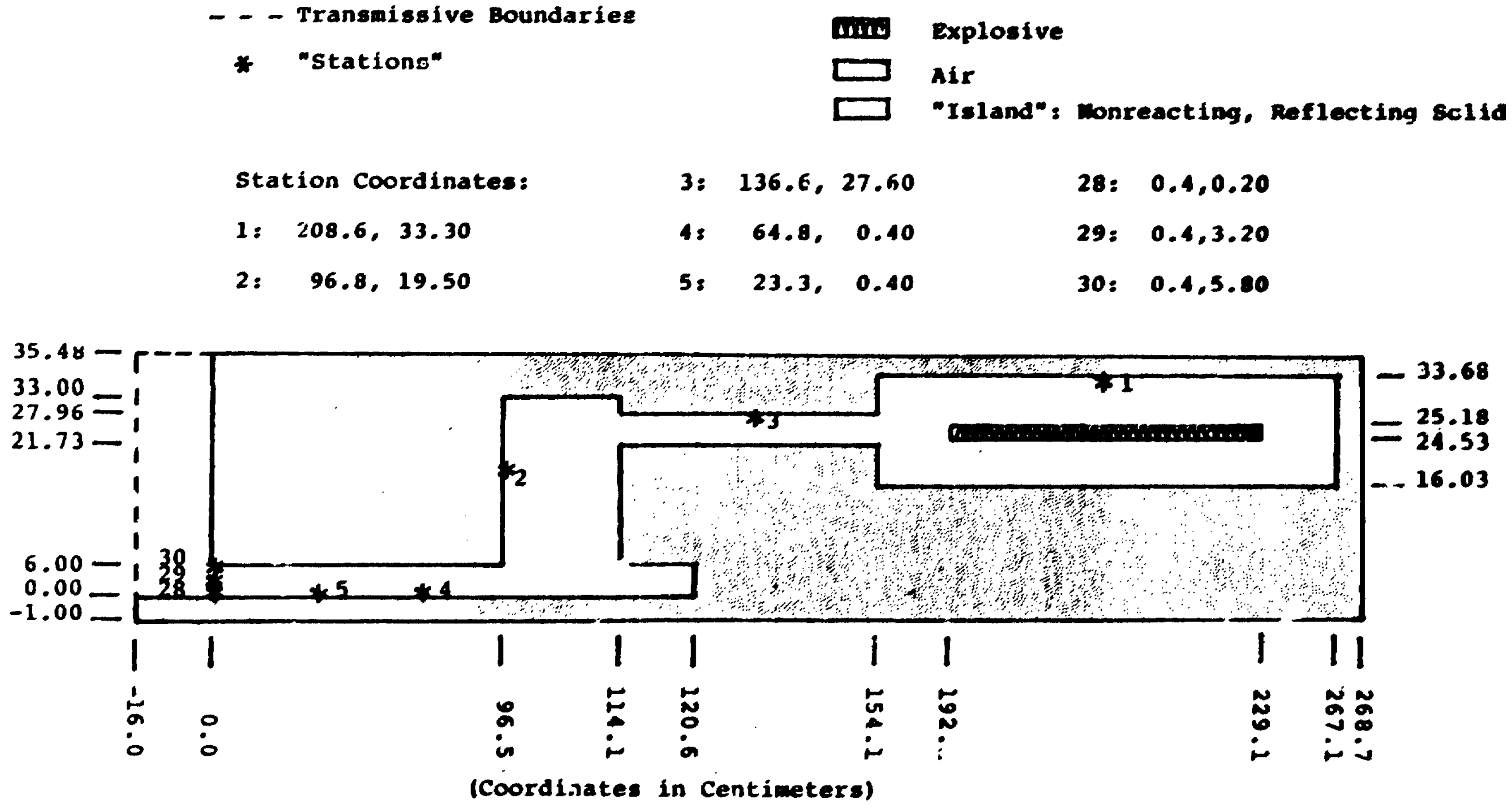
The calculation was done in four consecutive phases, which are described in the next four sections. Codes used were HULL, a two or three-dimensional, state-of-the-art, finite difference Eulerian hydrodynamic flow program; SAP (Spherical Air PUFF), a one-dimensional, spherically-symmetric version of HULL; and MLAWS, an acoustic wave propagation code. Using multiple phases in this way, efficiency of computer time is maximized while essential features of the result are retained. This summary report provides a description of the calculation and presents the results that were obtained.

II. PHASE 1: DETONATION AND INTERIOR PROPAGATION

The first phase of the calculation included detonation of an explosive in an enclosed region which was designed to simulate the interior tunnel complex of the NDCS test model. Propagation of blast waves in the enclosed chambers and exit of blast pressure at the tunnel mouth were monitored from time zero (initiation of the detonation) to 4.24 msec after detonation.

The calculational configuration used for this phase is illustrated in Figure 2. The calculational mesh is a rectangular grid in two-dimensions. The HULL code was used for this phase, as well as for Phase 2. In order to simulate the three-dimensional test chamber in two dimensions, it was necessary to change the orientations of the detonation and expansion chambers. In the test configuration, the entranceway and expansion chamber are oriented so that their long axes are horizontal and perpendicular to each other. The explosive chamber axis is vertical. In the calculational configuration, the right angle orientations are retained, but all chambers lie in the same plane.

Also because the coordinate system is rectangular while some of the test chambers have circular cross sections, it was necessary to adjust the dimensions slightly in order to maintain the appropriate cross-sectional areas and chamber volumes. If the unit depth (into the paper in Figure 2) is assumed to be 5 cm, then all of the chamber cross sections and volumes are the same



Station Coordinates:

1:	208.6, 33.30	3:	136.6, 27.60	28:	0.4,0.20
2:	96.8, 19.50	4:	64.8, 0.40	29:	0.4,3.20
		5:	23.3, 0.40	30:	0.4,5.80

Figure 2. **Schematic Diagram for Norwegian Underground Storage Bunker Calculation (Not to Scale).**

as for the test configuration. The total internal volume of the complex is 17,212 cm^3. Dimensions of the undetonated explosive were also adjusted so that, using the same 5-cm depth and a density of 1.66 gms/cm^3, the mass of the charge was 200 gms, corresponding to that used in the test. The explosive equation of state used was that for pentolite.

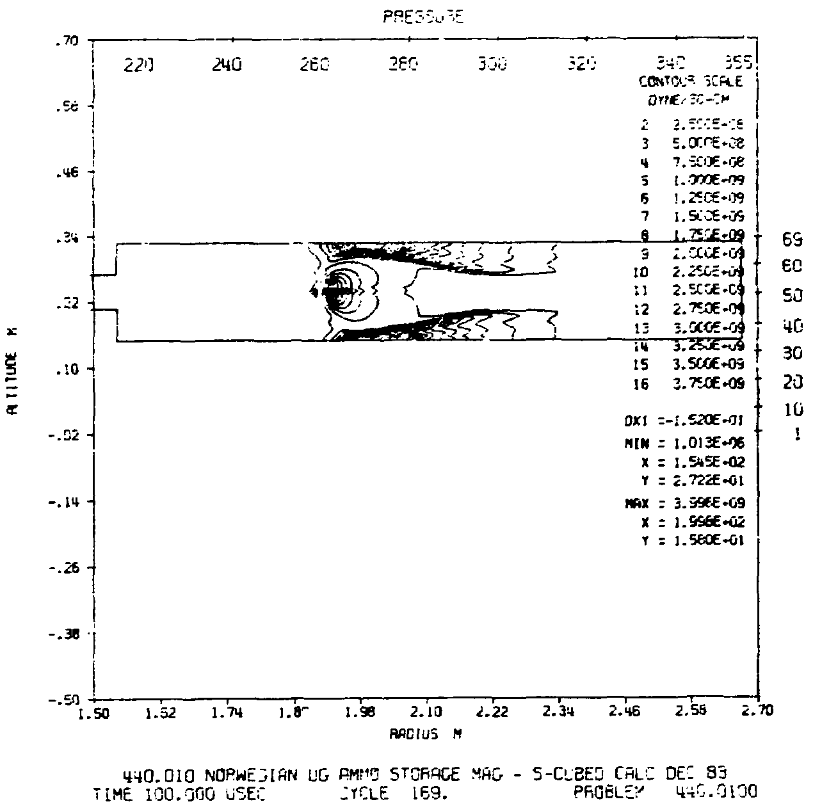
Grid size for this calculation is approximately 0.5 cm vertically by 0.6 cm horizontally, although adjustments were made so that cell boundaries would coincide with the previously determined material boundaries. There are 70 x 376, or approximately 26,000, calculational cells in the grid.

The calculation was begun [illegible] time set arbitrarily to 10 µsec. At this time, the calculational zone at the right-hand edge of the explosive was considered to be detonated. The detonation wave progressed through the explosive from right to left as the calculation proceeded.

Two types of graphical output are routinely provided by HULL, and selected examples are included in this report. The first is "contour" plots, in which isograms of any of the hydrodynamic variables are shown throughout the region of interest. Figures 3 through 10 are contour plots of pressure and energy at four different times during the interior calculation. In Figures 3 and 4, at 100 µsec, it can be seen that the explosive is detonating but the energy has not yet started to escape from the explosive chamber. Pressure and energy values in the chamber are very high.

In Figures 5 and 6, at 300 µsec, a shock wave has traveled through the narrow passageway, reflected from the left-hand side of the vertical chamber, and is moving downward. Pressures are high at the top and left-hand sides of the vertical chamber where the flow has stagnated, and reflected shocks from the corners are visible in the explosive chamber.

The next two figures, 7 and 8, illustrate the situation at 500 µsec. At this time, energy is moving down the long entrance tunnel. The interesting



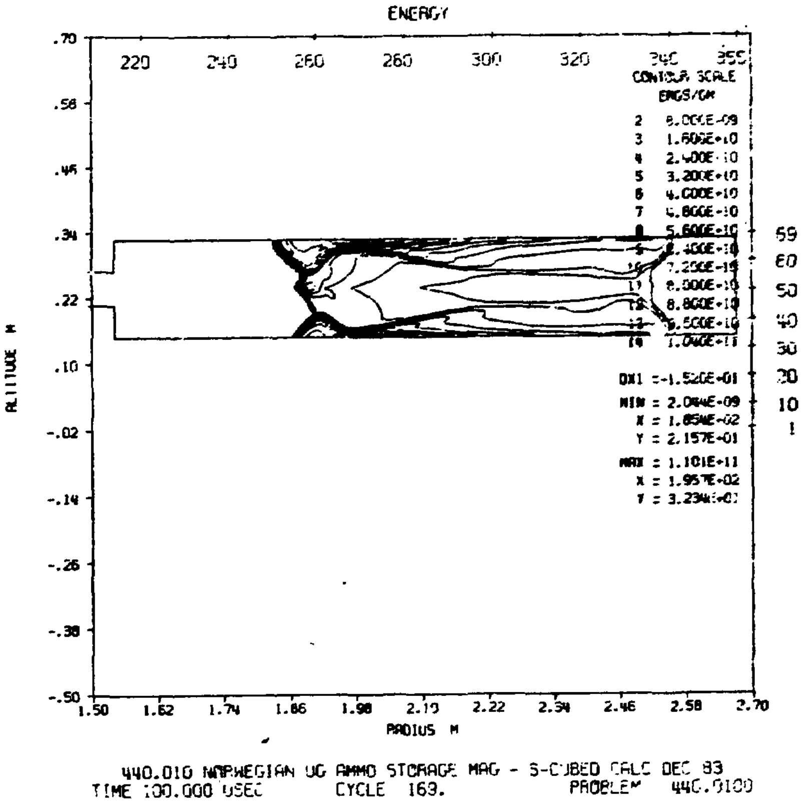


Figure 3. **Pressure Contours in Explosive Chamber at 100 μsec after Detonation.**

Figure 4. **Energy Contours in Explosive Chamber at 100 μsec after Detonation.**

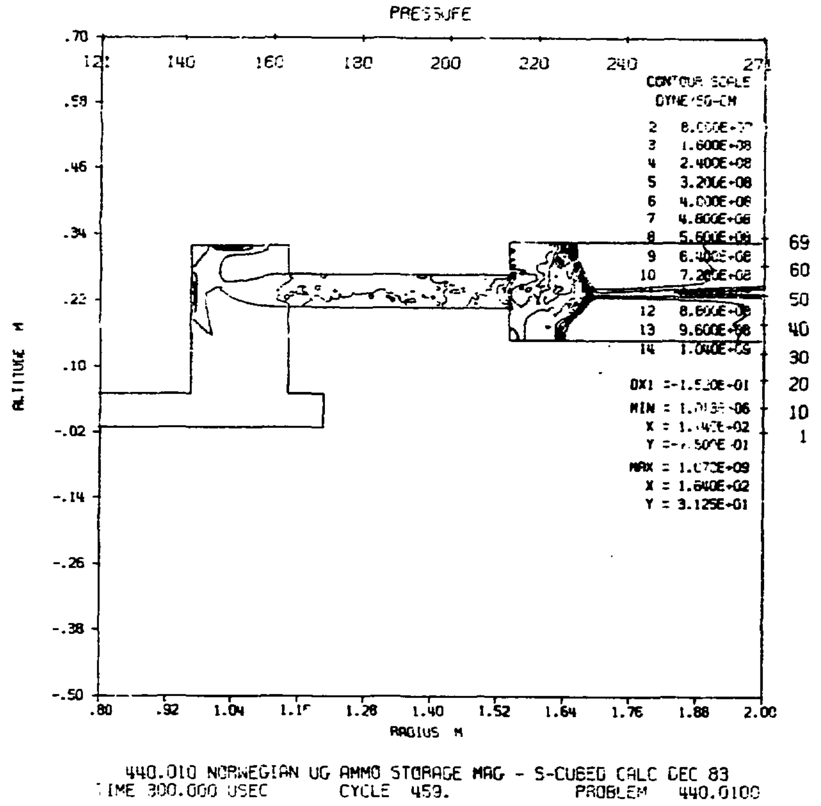


Figure 5. Pressure Contours in Vertical Chamber and Passageway at 300 μsec after Detonation.

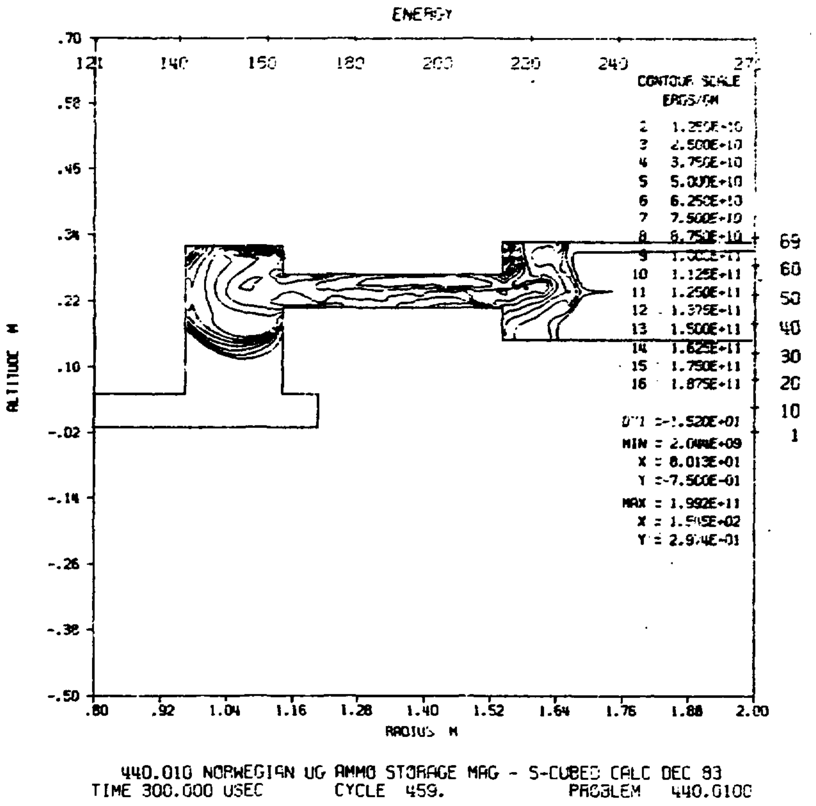


Figure 6. Energy Contours in Vertical Chamber and Passageway at 300 μsec after Detonation.

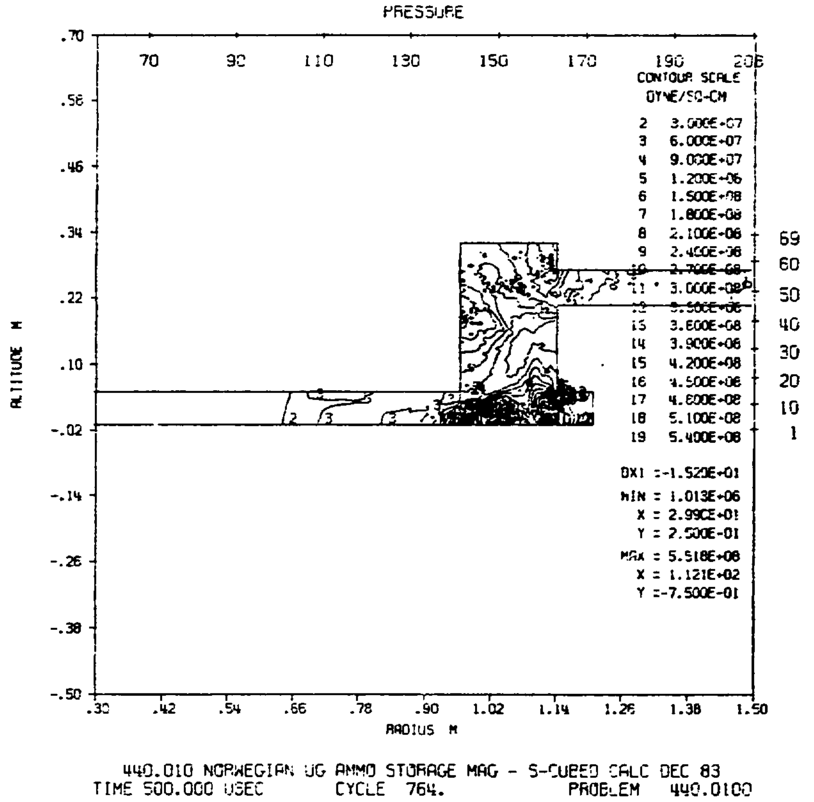


Figure 7. Pressure Contours in Vertical Chamber and Entrance Tunnel at 500 μsec after Detonation.

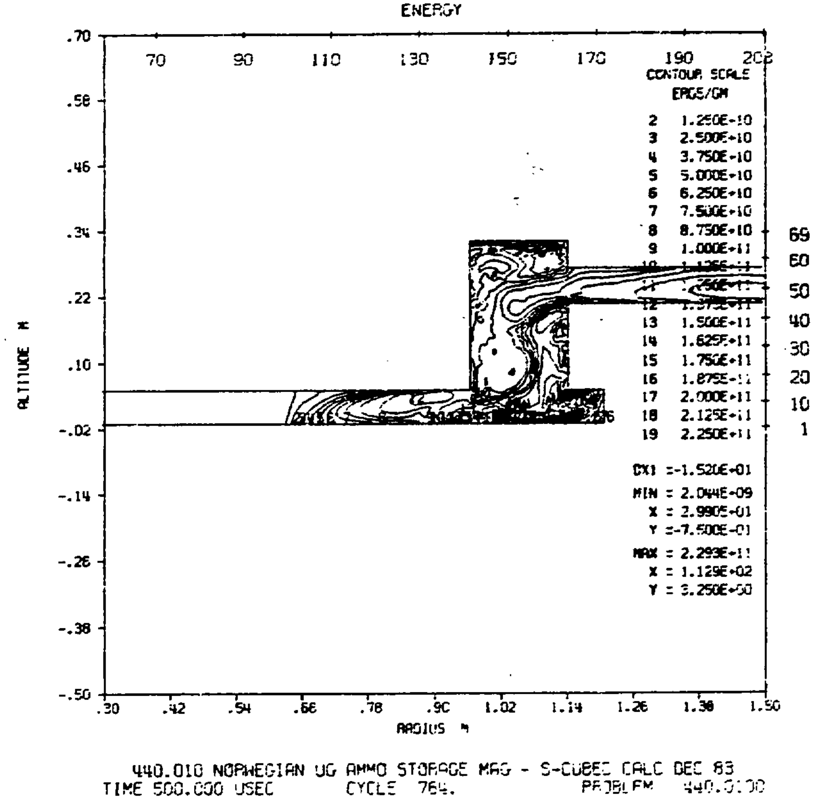
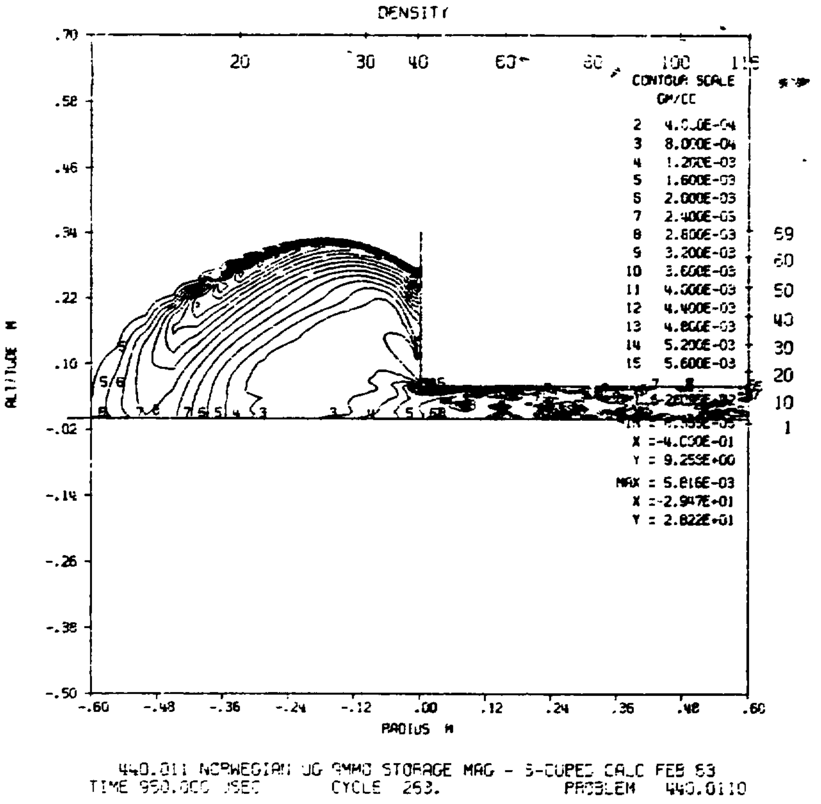


Figure 8. Energy Contours in Vertical Chamber and Entrance Tunnel at 500 μsec after Detonation.



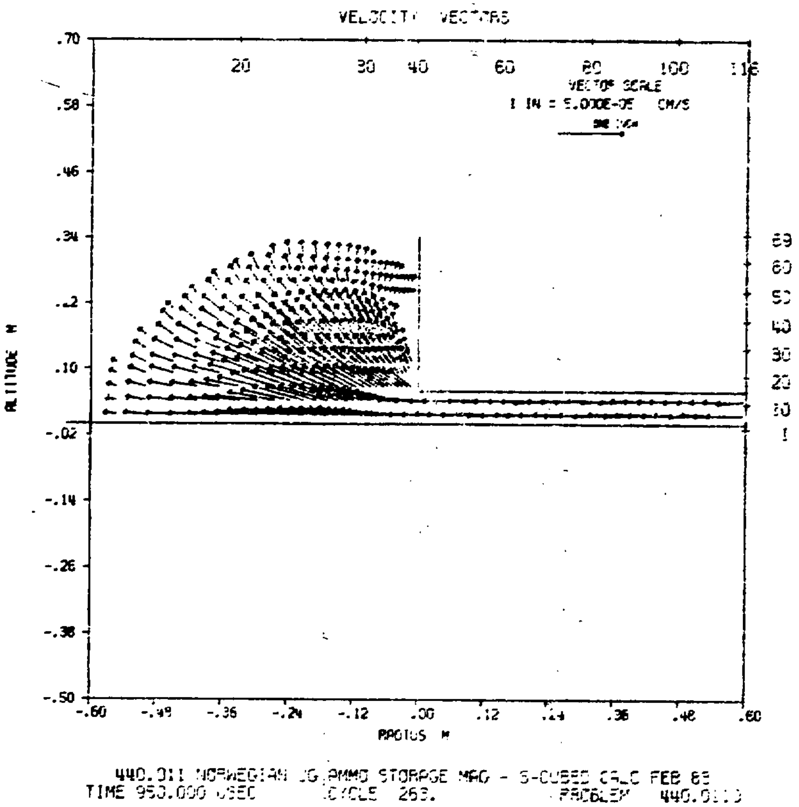


Figure 9. Density Contours in Tunnel Entrance Region at 950 μsec after Detonation.

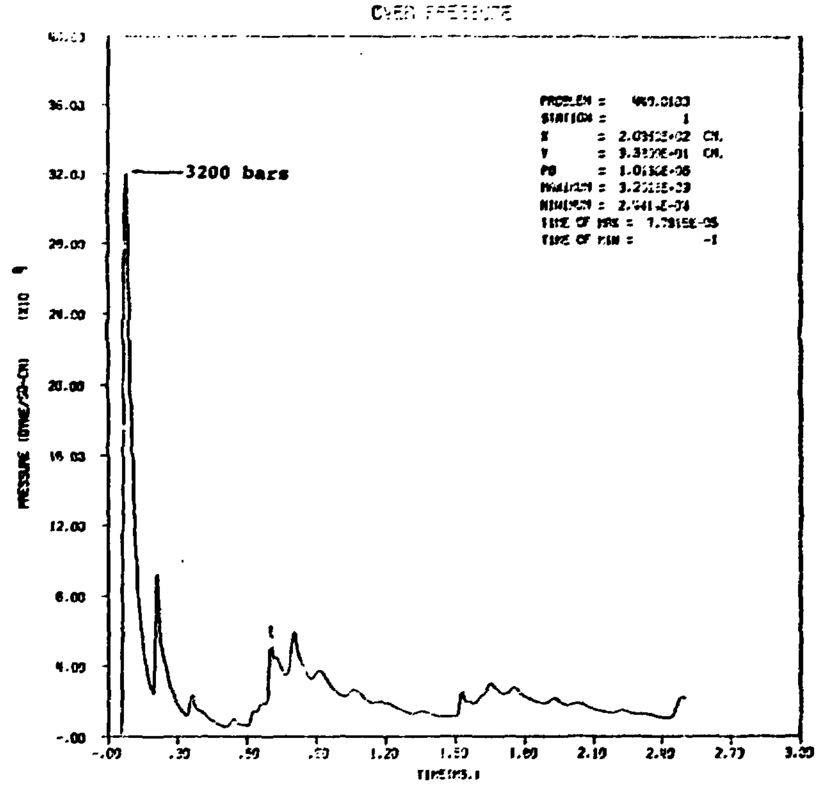
Figure 10. Velocity Vectors in Tunnel Entrance Region at 950 μsec after Detonation.

point about the flow in this region is that the energy contours are not perpendicular to the tunnel walls. Because of the right-angle bend, energies are higher near the bottom of the tunnel.

The last set of contour plots was made at 950 μsec, and is shown in Figures 9 and 10. In this set, the shock has reached the tunnel entrance and is expanding as it moves into the exterior space. Density contours and velocity vectors are given instead of pressure and energy contours in this case. The interesting thing about Figure 10 is that motion is shown curling back toward the wall near the top of the plot.

The second type of output is probably of more immediate interest in this application because it is directly comparable to experimental results. "Stations" are predetermined locations in the calculational grid at which hydrodynamic data are monitored as functions of time. For the interior phase calculation, stations were placed at measuring points corresponding to those in the NDCS test. These are the points labeled 1 through 5 in Figure 2. Additional stations were positioned at the tunnel entrance and at other points throughout the calculational grid. Stations 28, 29 and 30 are of particular interest because they are the ones used to drive the second phase of the calculation. Their locations are also shown in Figure 2.

Figures 11 through 15 are overpressure versus time records at Stations 1 through 5. The first three, which are in the explosive and vertical chambers and the connecting tunnel between them, show a large initial spike followed by many smaller peaks. The latter are due to reflections from the chamber walls. Stations 4 and 5, for which the overpressure records are shown in Figures 14 and 15, are located in the entrance tunnel. The records show many sharp spikes, which are a result of the mixture of air and detonation products flowing in this region. The maximum overpressure in the entrance tunnel is about 80 bars. In Figure 15, an experimental record from Measuring Point 5 is also shown (the dashed line), but the maximum measured overpressure value is only about 58 bars.



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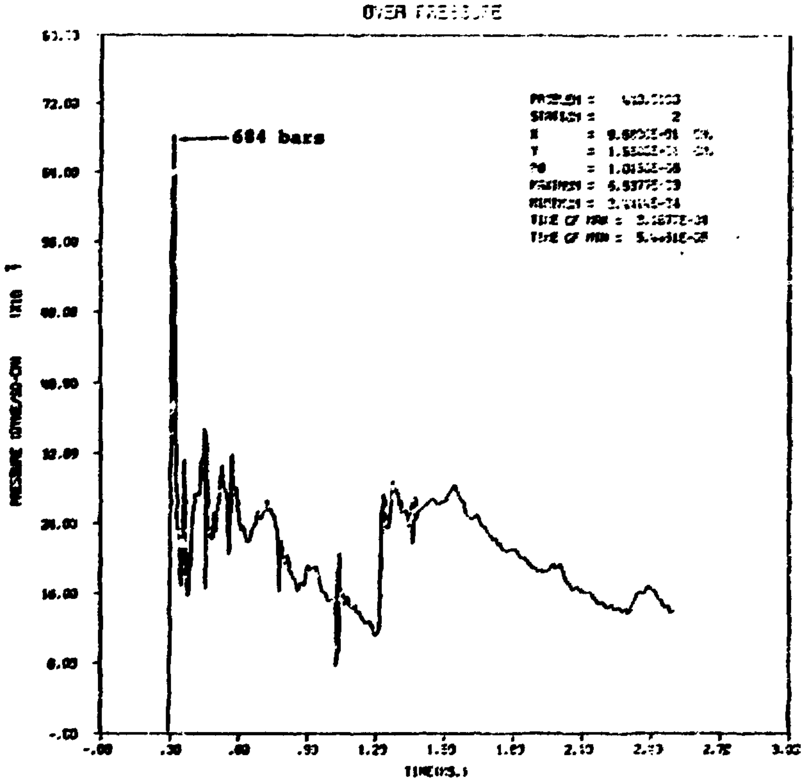

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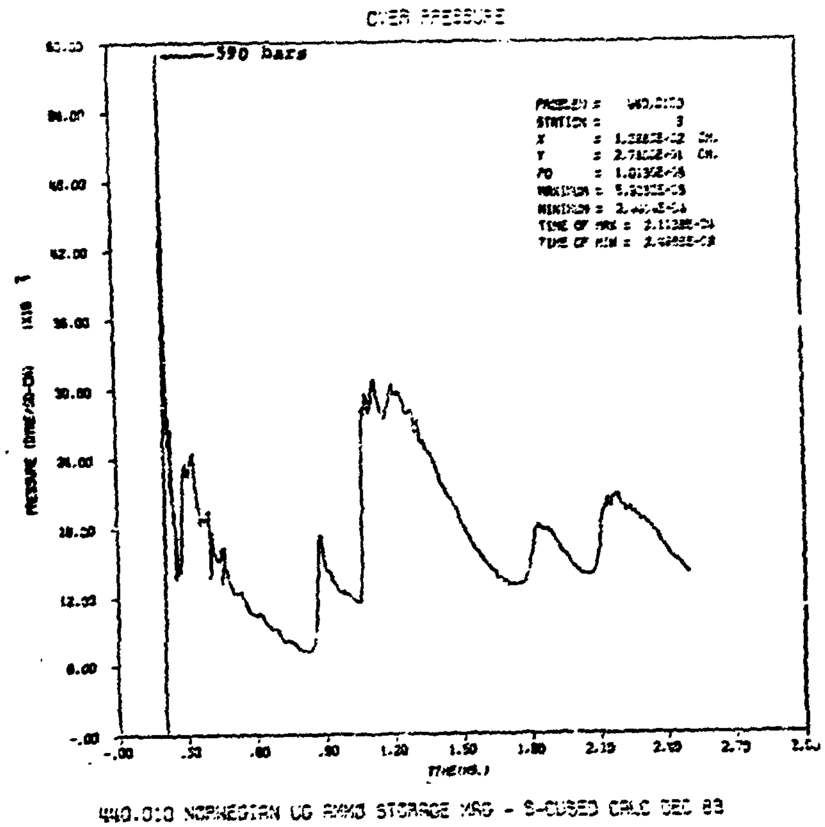
Figure 11. Overpressure versus Time Record at Measuring Point 1.

Figure 12. Overpressure versus Time Record at Measuring Point 2.



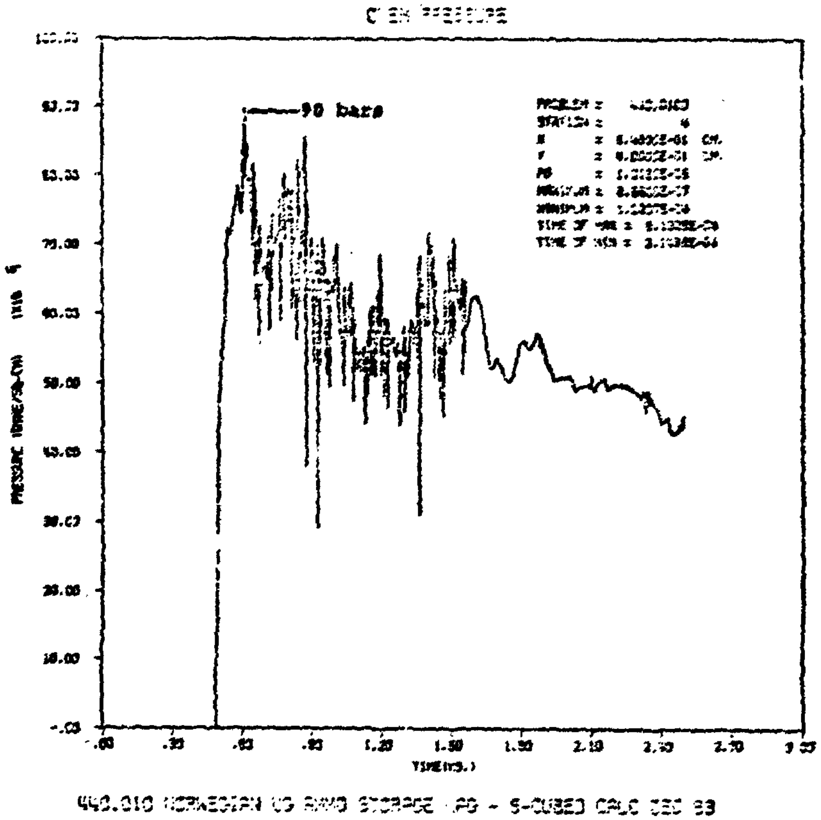
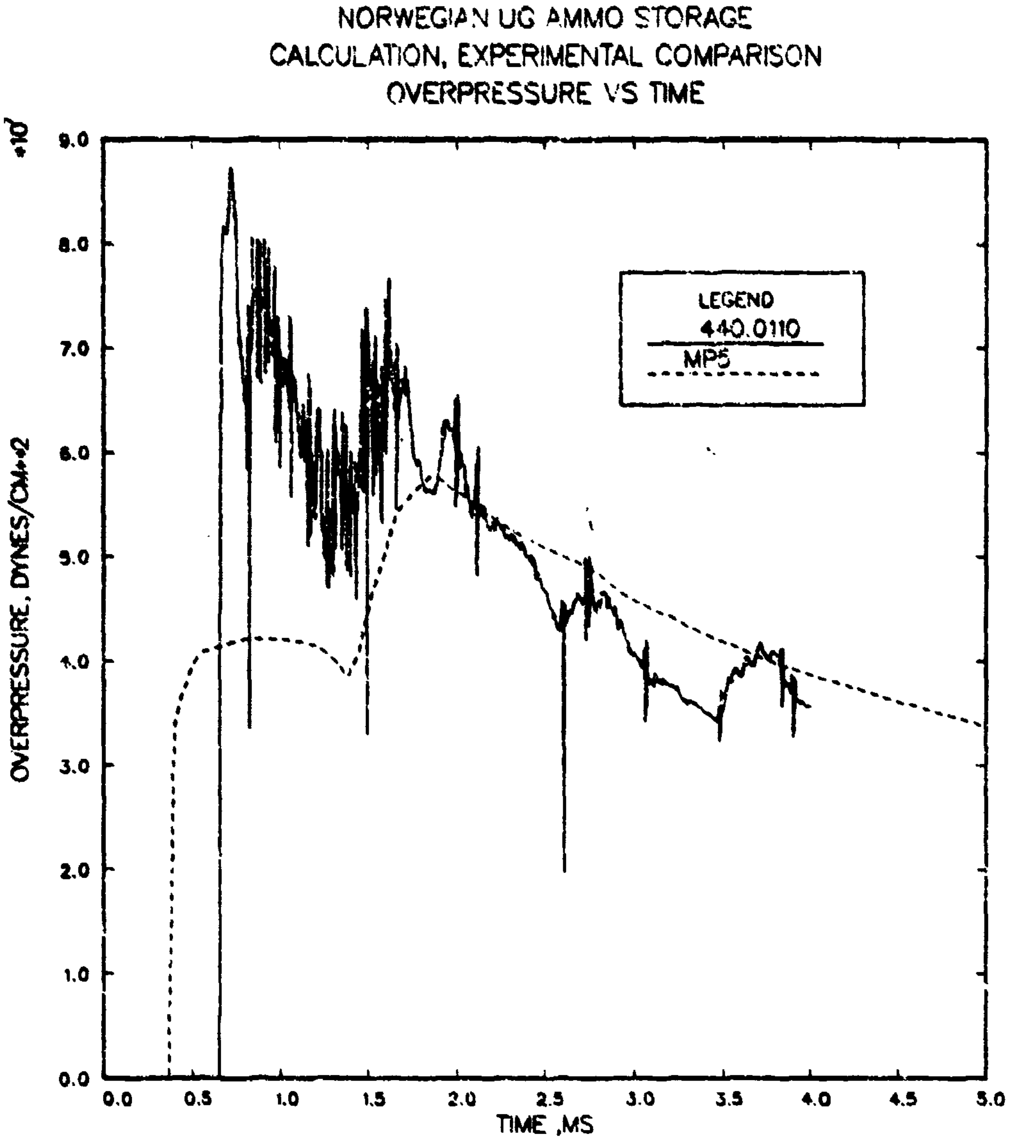


Figure 13. Overpressure versus Time Record at Measuring Point 3.

Figure 14. Overpressure versus Time Record at Measuring Point 4.


NORWEGIAN UG AMMO STORAGE
CALCULATION, EXPERIMENTAL COMPARISON
OVERPRESSURE VS TIME

440.0110 5; COORD: 2.330E+01 4.000E-01 FT; TOA: 6.600E-01 MS
NDCS MP5, TOA: .35 MS

Figure 15. Overpressure versus Time Record at Measuring Point 5, with Experimental Data (Dashed Line).

Parameters at the tunnel entrance (Stations 28, 29 and 30) are shown in Figures 16 through 21. For these stations, the horizontal flow velocities versus time are given as well as the overpressures. Note that these velocities are negative because flow through the portal is in the "-x" direction.

III. PHASE 2: EXPANSION INTO EXTERIOR REGION

In order to model the exterior region, a computational mesh was set up using cylindrical coordinates. The mesh consists of 182 x 178 zones, for a total of 31,304. The overall grid dimensions are 5.96 m by 5.99 m. A 100 x 100 cell subgrid, in which the size of each cell is approximately 0.49 x 0.8 cm, was defined on the cylindrical axis at the tunnel opening. Beyond the subgrid, cell size is expanded by about 5 percent per cell in each direction. Stations were located at intervals along radial lines from the tunnel exit.

The configuration is illustrated in Figure 22. For this phase, a plane through the axis of symmetry, which can be thought of as a flat, perfectly reflecting surface, becomes the ground plane. The tunnel opening and cliff face become cylindrical sections when converted from Cartesian to cylindrical coordinates. The radius of the opening was adjusted so that the cross-sectional area of the half-disk opening in cylindrical coordinates is equal to the rectangular 5 x 6 cm tunnel opening of Phase 1.

The cliff face was modeled by placing a row of "island" cells along the bottom of the mesh. An island is a non-compressible, reflective cell of the same type as was used in Phase 1 for the tunnel walls. The configuration, it should be noted, is rotated by 90 degrees from that of Phase 1, so that direction of flow is upward in Figure 22.

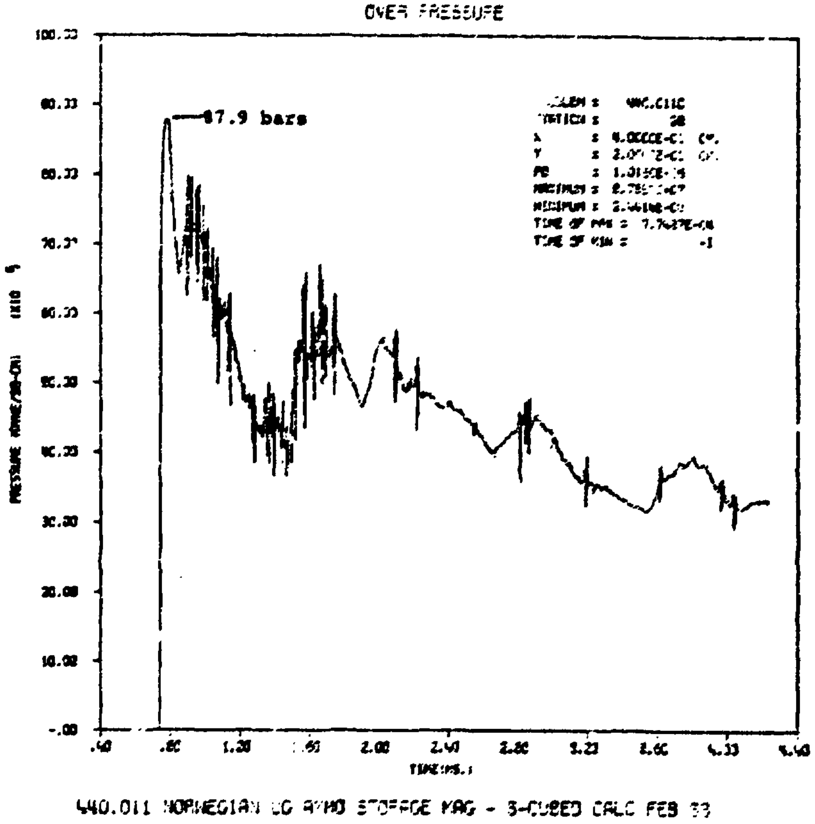


Figure 16. Overpressure versus Time Record at Tunnel Entrance, Near the Floor.

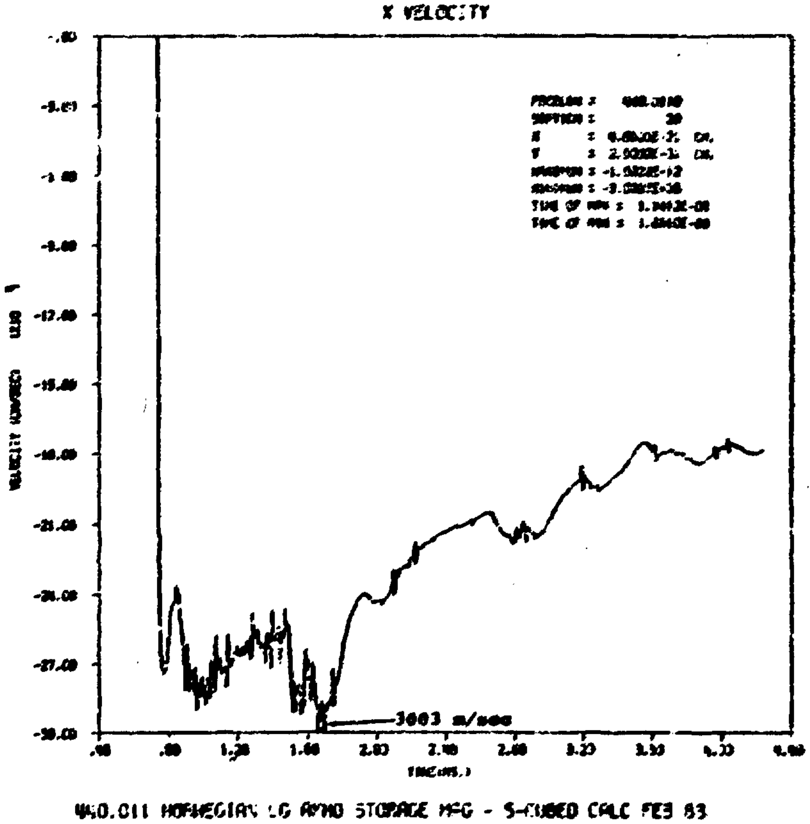


Figure 17. Horizontal Velocity versus Time Record at Tunnel Entrance, Near the Floor.

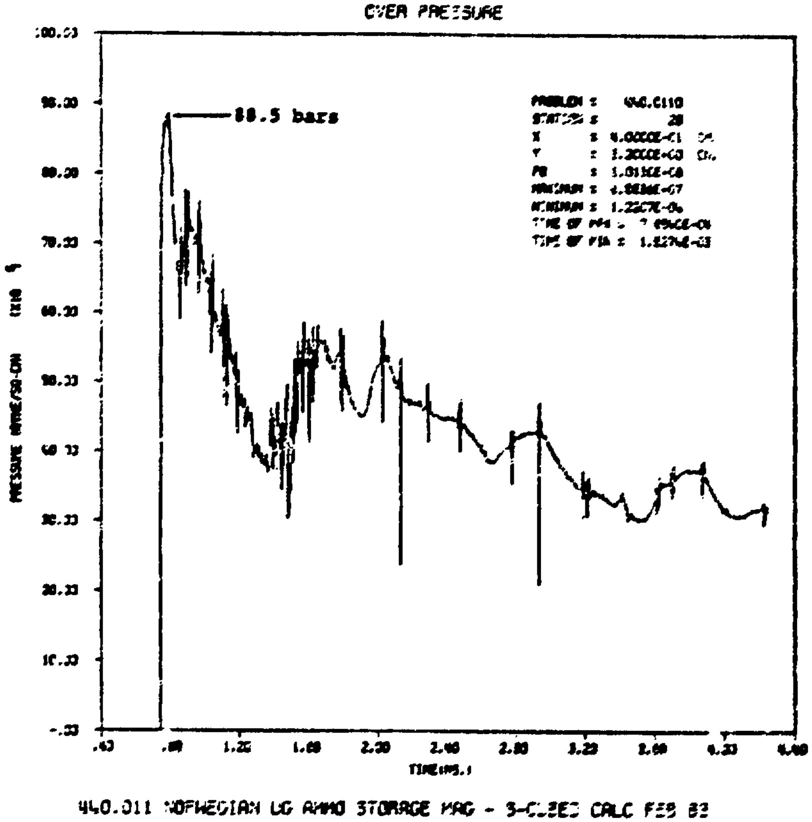


Figure 18. Overpressure versus Time Record at Tunnel Entrance, Near the Center.

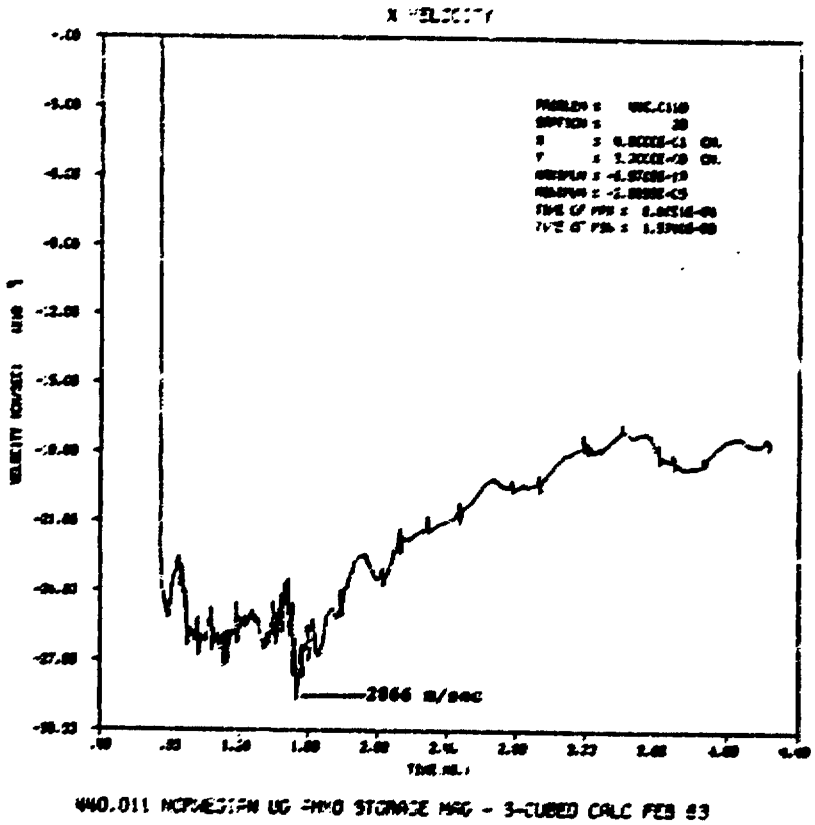


Figure 19. Horizontal Velocity versus Time Record at Tunnel Entrance, Near the Center.

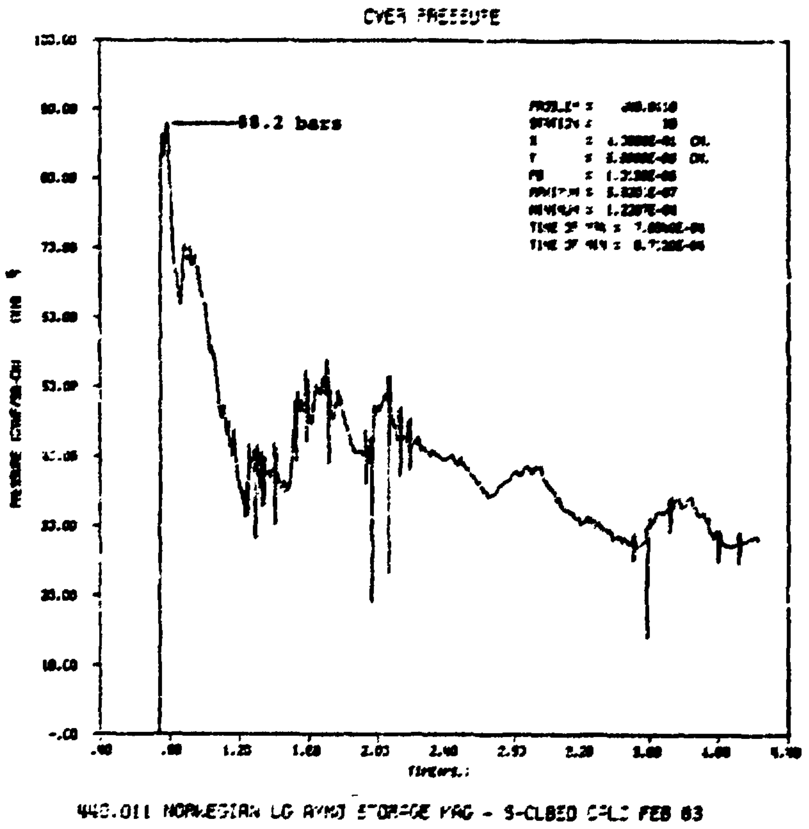


Figure 20. Overpressure versus Time Record at Tunnel Entrance, Near the Roof.

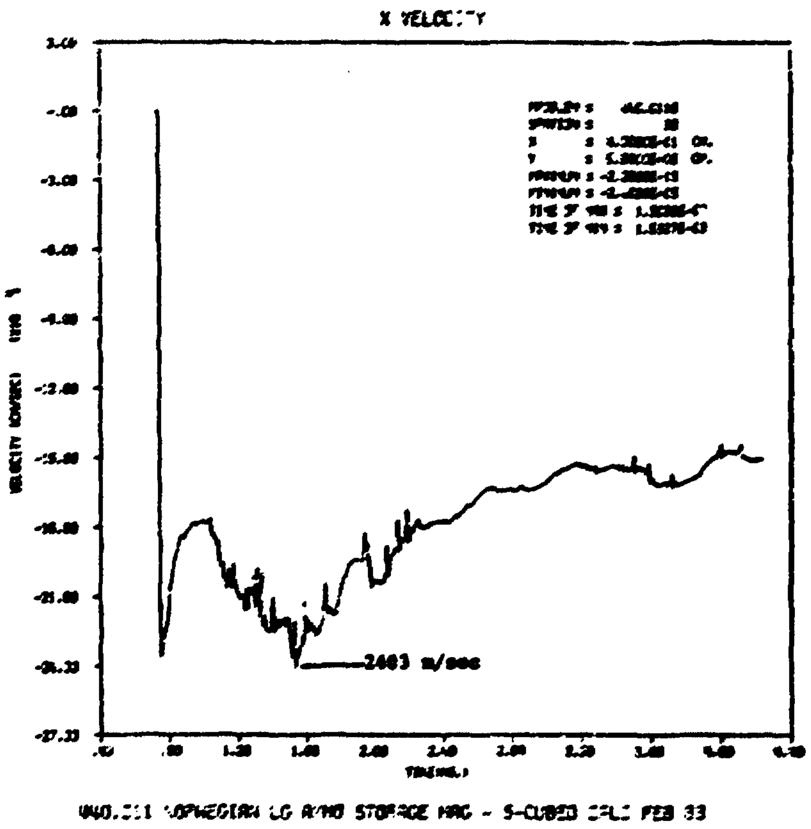


Figure 21. Horizontal versus Time Record at Tunnel Entrance, Near the Roof.

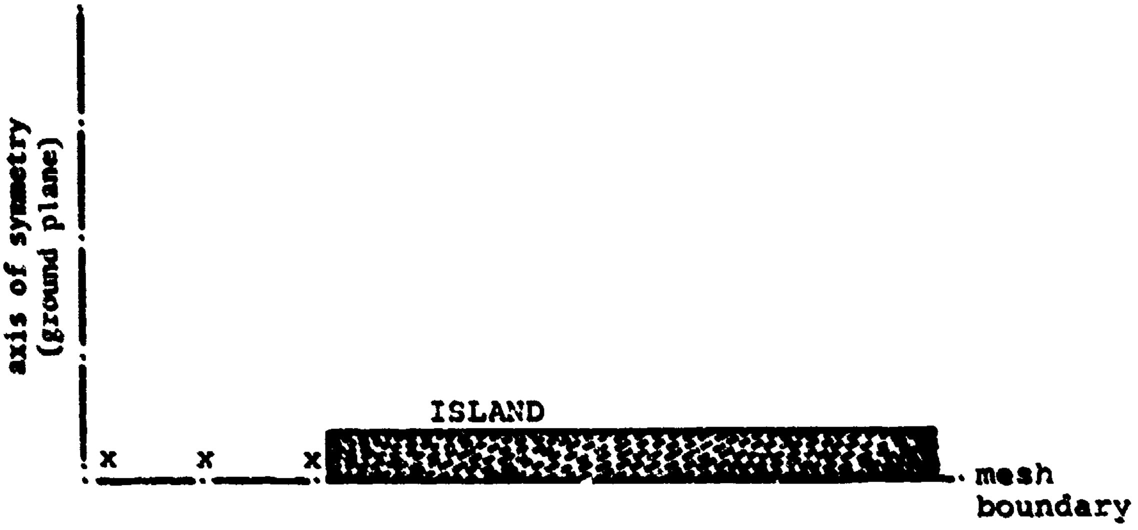


Figure 22. Calculational Configuration for Phase 2.

The calculation was initiated at 0.7 msec by setting the hydrodynamic parameters in the cells at the tunnel opening to those read from the station records of Phase 1. To perform the transformation, the "-x" velocities of the Phase 1 station records become the "+y" velocities of the Phase 2 driver cells, and +y's became +x's. Interpolation was performed to drive the cells at locations between stations at appropriate values.

The second phase calculation was run to 3.1 msec after detonation of the explosive. By this time, the shock wave emerging from the tunnel opening had traveled a distance of 1.75 m (5.74 ft) along the axis and had decayed to an overpressure of approximately 1.0 bar (14.5 psi). Figures 23 through 28 illustrate the pressure, density, and energy at two different times (1.5 and 2.3 msec) during the calculation. An interesting feature shown by the pressure and density plots is the development of a Mach-stem-like structure at the interaction with the cliff face. The structure, usually observed only with height-of-burst detonations, is an indication of flow toward the surface

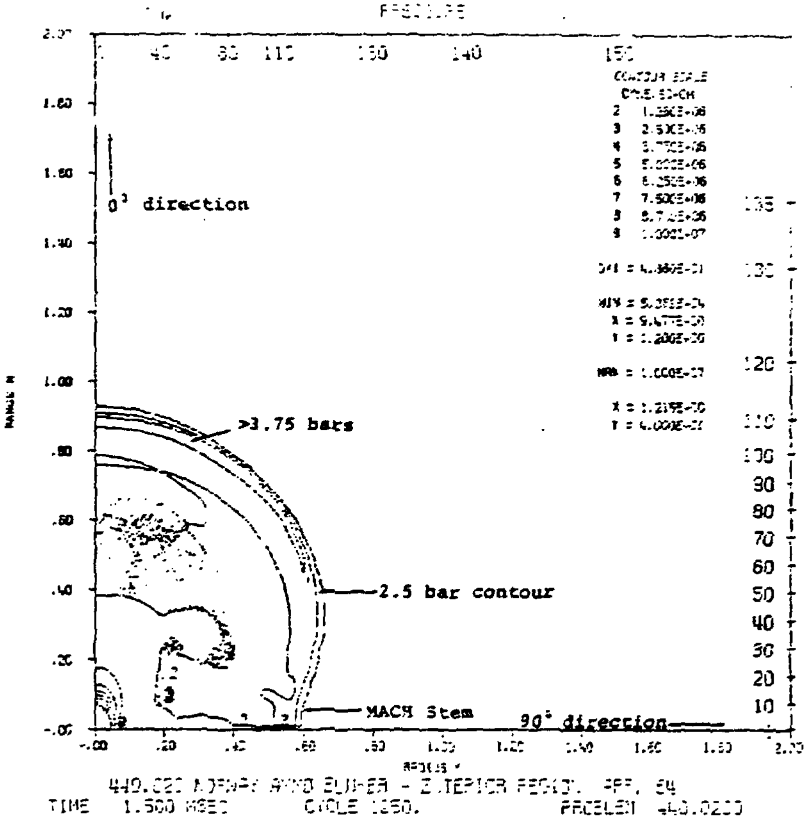


Figure 23. Pressure Contours in Exterior Region at 1.5 msec after Detonation.

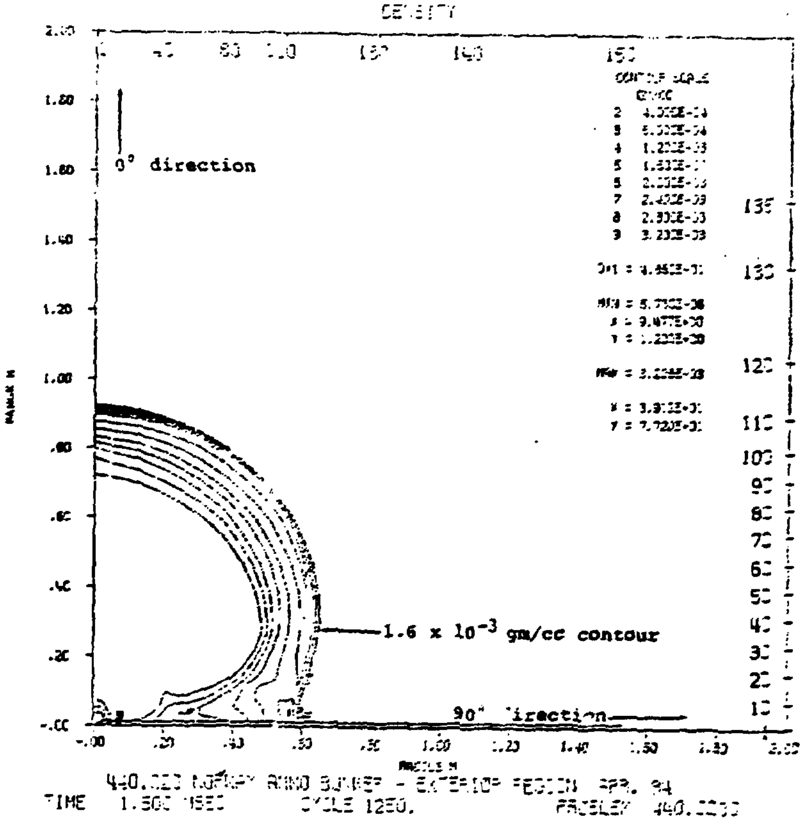


Figure 24. Density Contours in Exterior Region at 1.5 msec after Detonation.

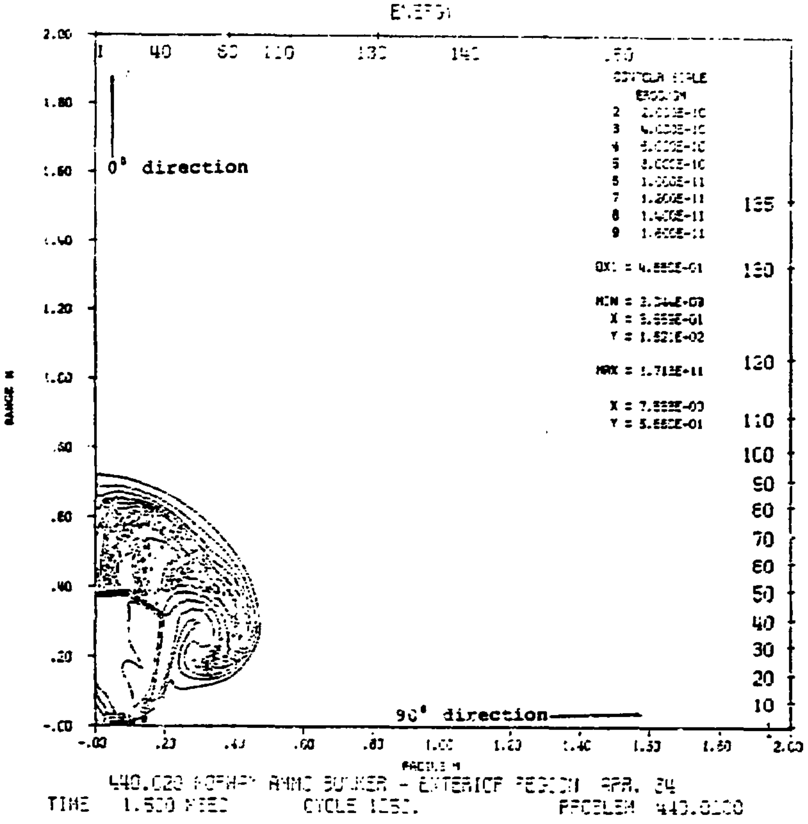


Figure 25. Energy Contours in Exterior Region at 1.5 msec after Detonation.

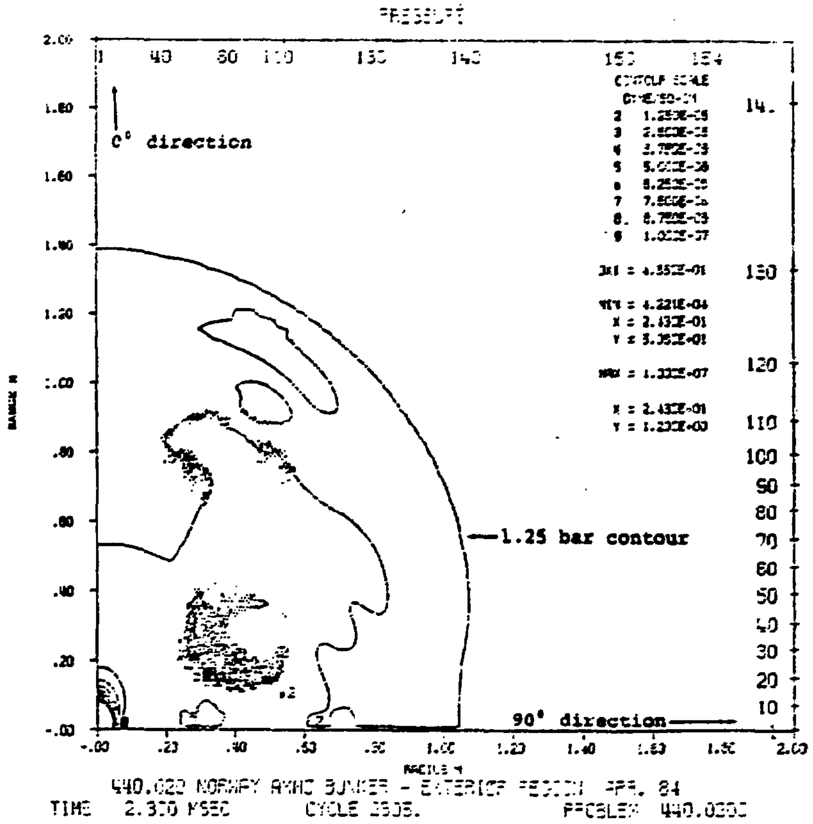


Figure 26. Pressure Contours in Exterior Region at 2.3 msec after Detonation.

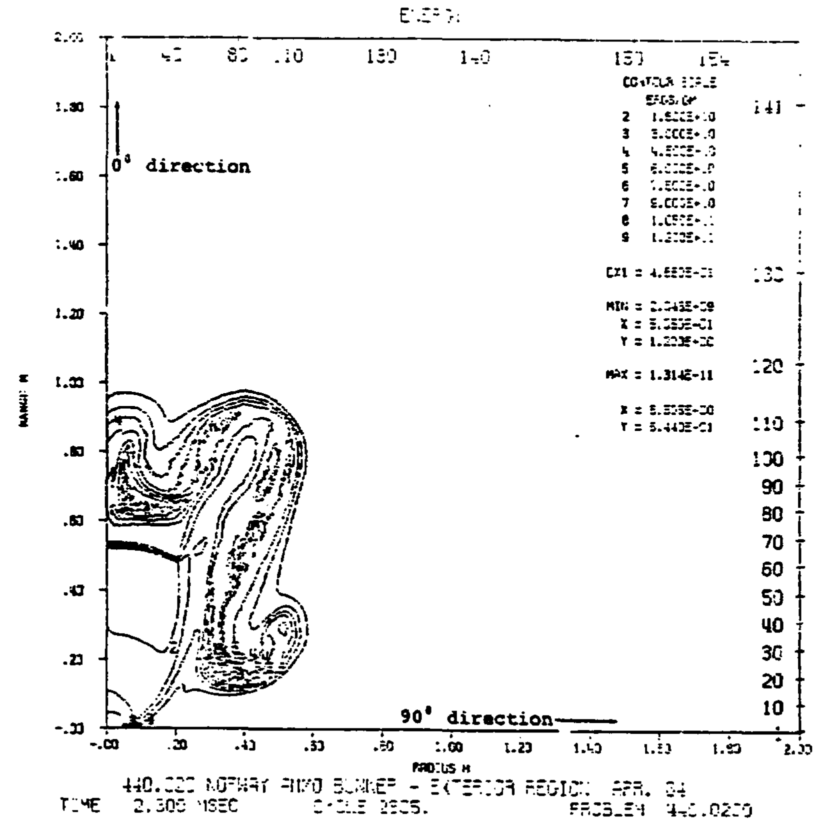


Figure 27. Density Contours in Exterior Region at 2.3 msec after Detonation.

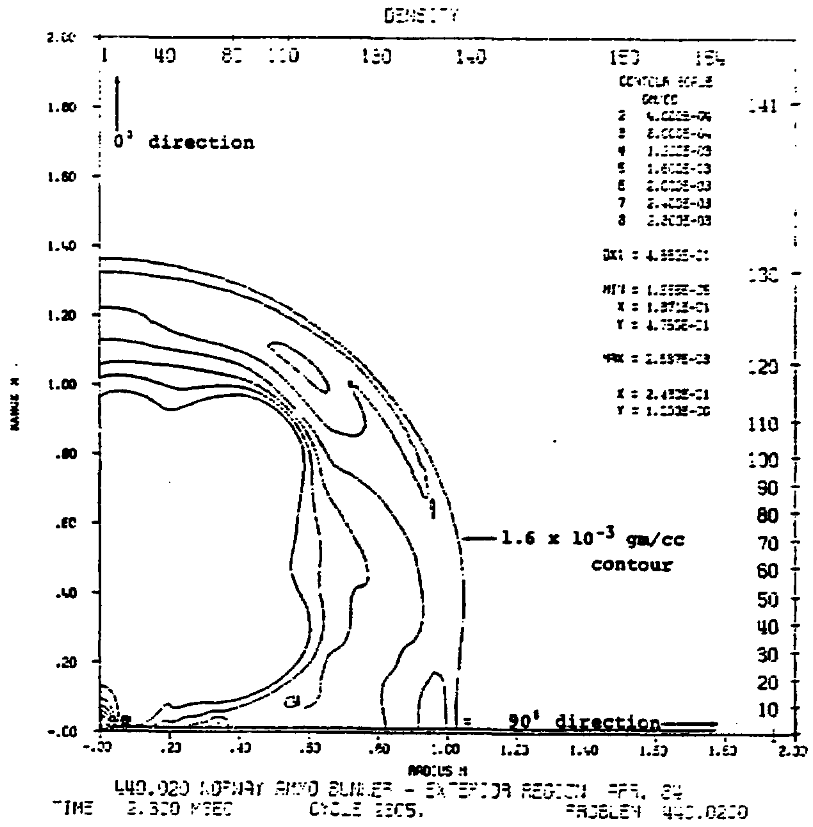


Figure 28. Energy Contours in Exterior Region at 2.3 msec after Detonation.

(downward in the picture) as well as parallel to the surface. An indication of this kind of flow was seen in the vector velocity plot of Phase 1 (Figure 10).

IV. PHASE 3: ONE-DIMENSIONAL CALCULATIONS

Phase 3 consists of a series of one-dimensional calculations along lines radiating from the tunnel entrance. The Phase 3 calculations were done using SAP (Spherical Air Puff), S-CUBED's version of the one-dimensional Eulerian, spherical-symmetry hydrocode originally developed at the Air Force Weapons Laboratory (AFWL).

At 3.1 msec, as previously mentioned, the Phase 2 two-dimensional calculation was terminated. It was replaced by a series of one-dimensional calculations along the lines A through G shown in Figure 29. The initial

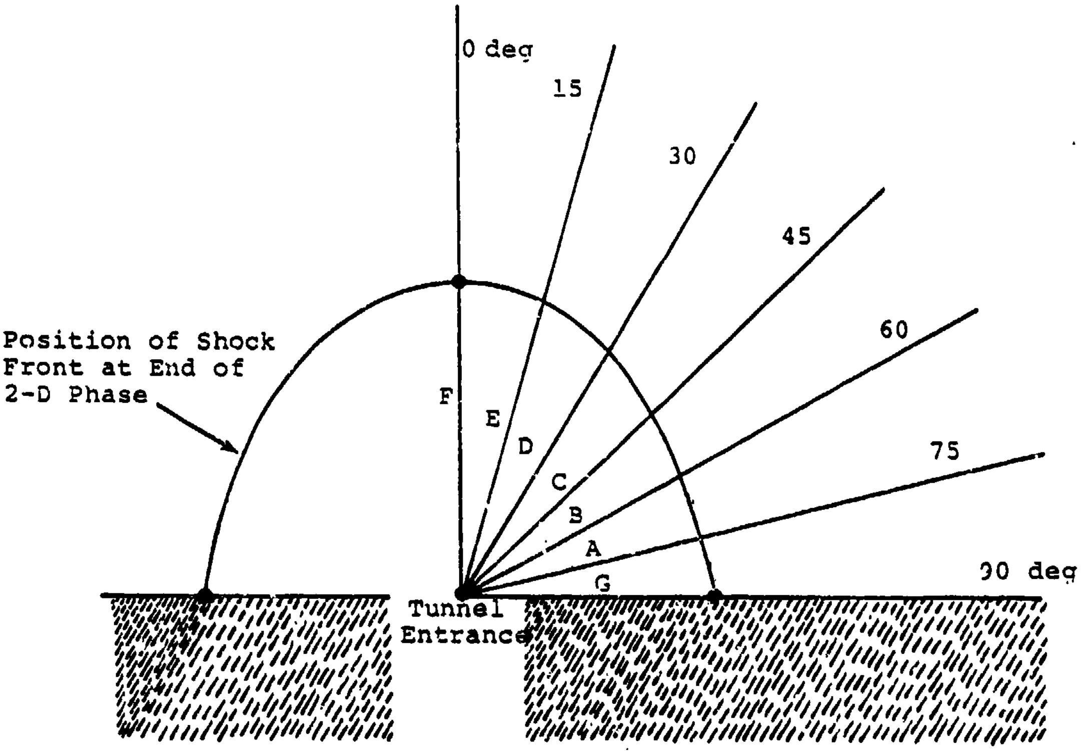


Figure 29. Calculational Configuration Showing Lines Along Which One-Dimensional Calculations Were Performed.

conditions for each Phase 3 calculation were obtained by "cutting" through the Phase 2 calculational mesh at 3.1 msec. Energy, density and velocity values were read from zones through which the lines passed. Interpolation across four adjacent zones was performed in order to obtain values along the lines. Also, the component x and y velocities were combined to determine the appropriate velocity in the direction of the line cut. Phase 2 contour plots at 3.1 msec, which were used to provide the initial conditions, are given in Figures 30 through 33. The lines along which the cuts were taken (approximately every 15 deg) are shown in Figure 30.

As each of the SAP calculations proceeded in time, the waveform defined by the cut was allowed to propagate outward. The innermost cell was continually reset to conditions from the late-time record for Station 29 (Phase 1). The one-dimensional calculations were continued until a shock front peak overpressure of less than 250 mbar, or 3.62 psi, was reached. This occurred at times between 12.0 and 12.5 msec. After 4.2 msec, when the Station 29 record ended, constant values of the parameters equal to those at the last time for Station 29 (4.2 msec) were maintained at the inner edge of the SAP grid.

Figures 34 through 40 are overpressure versus range plots, one for each of the seven SAP calculations, at the final time for that calculation. These range plots provided the waveforms from which inputs for NLAWS, the acoustic wave propagation code used in Phase 4, were defined.

V. PHASE 4: NONLINEAR ACOUSTIC WAVE SOLUTION (NLAWS)

NLAWS is a code which treats the airblast waveform as an acoustic wave. The code assumes an ideal triangular waveform input with an infinitely sharp rise to a positive overpressure and then a monotonic decay to zero. The triangular wave is then propagated acoustically until it has attenuated to

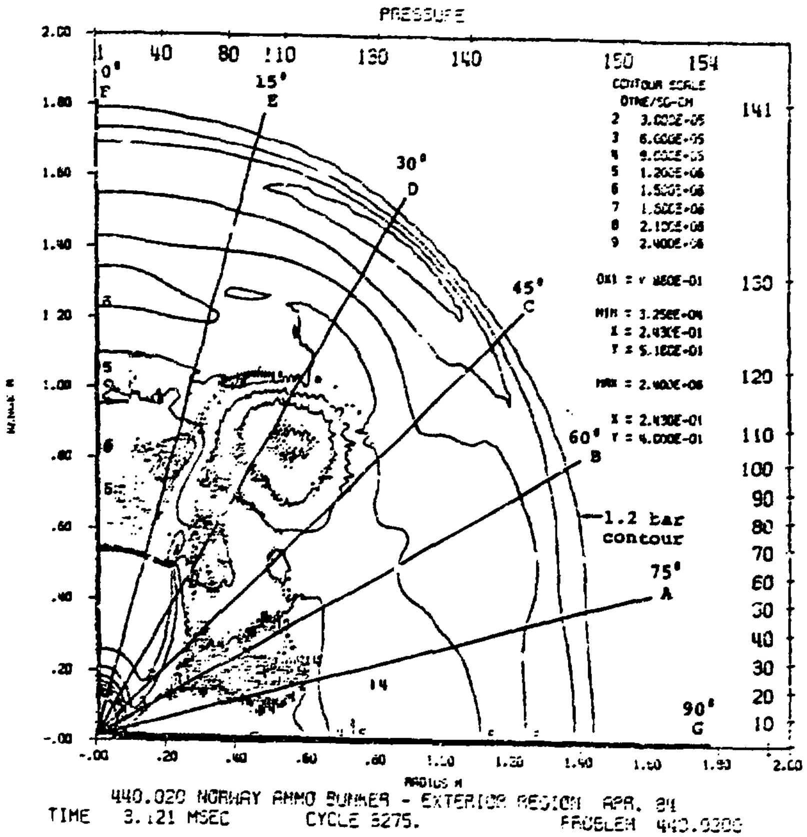


Figure 30. Pressure Contours at 3.1 msec Used for Initiation of Phase 3.

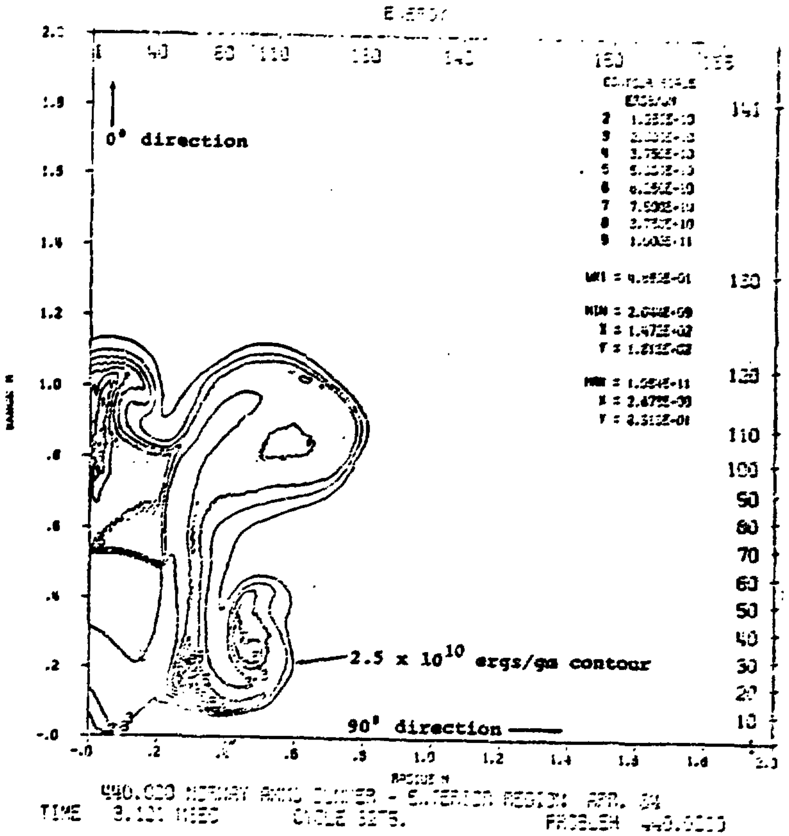


Figure 31. Energy Contours at 3.1 msec Used for Initiation of Phase 3.

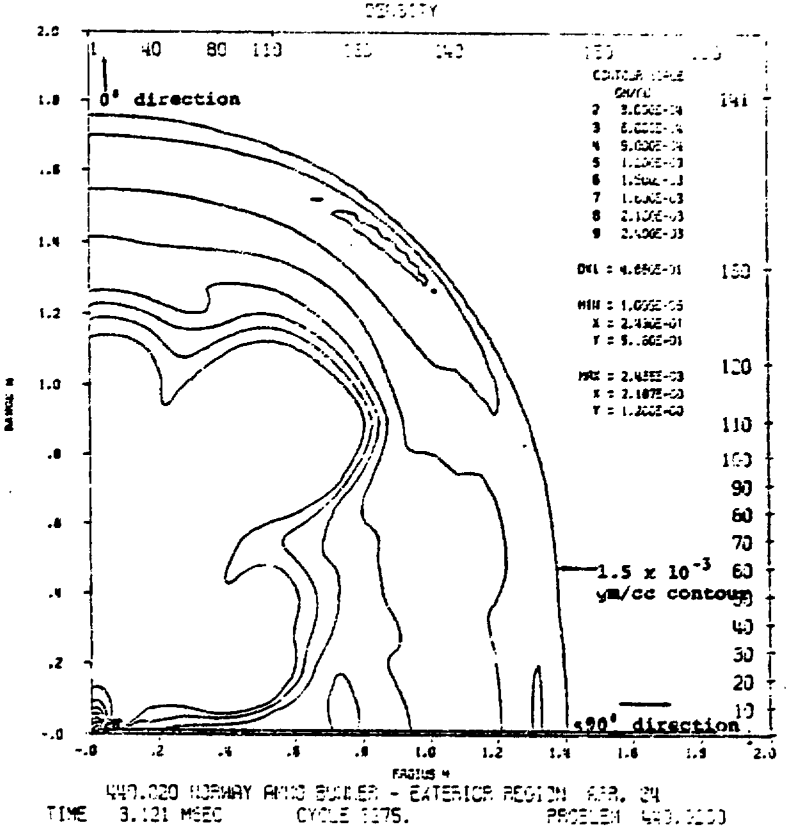


Figure 32. Density Contours at 3.1 msec Used for Initiation of Phase 3.

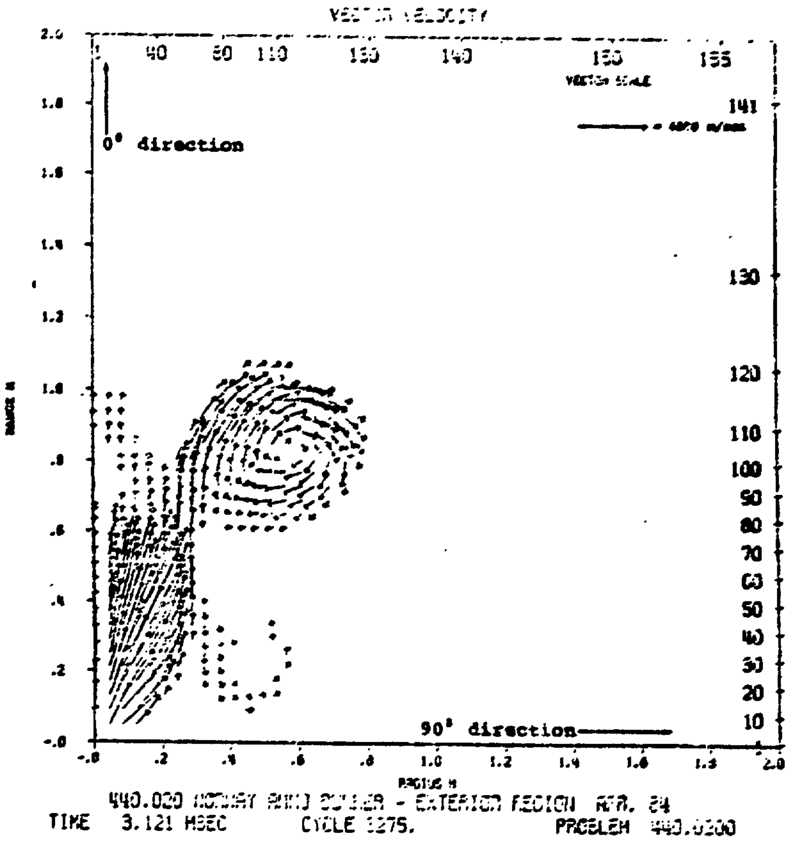


Figure 33. Flow Velocity Vector Plot at 3.1 msec Used for Initiation of Phase 3.

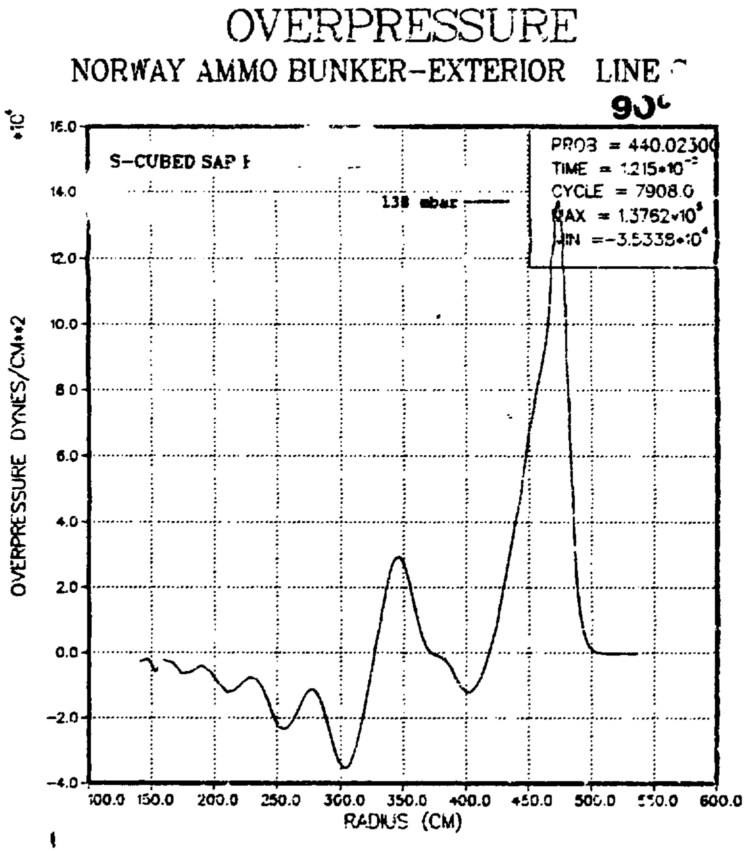


Figure 34. **Overpressure versus Range Plot Along 90° Line at 12.15 msec.**

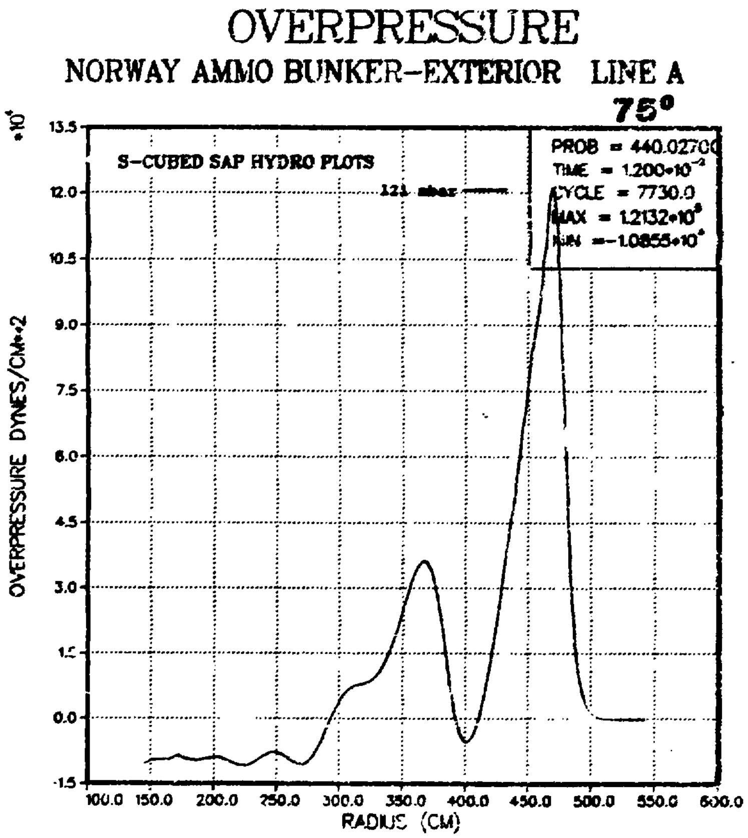


Figure 35. **Overpressure versus Range Plot Along 75° Line at 12.00 msec.**

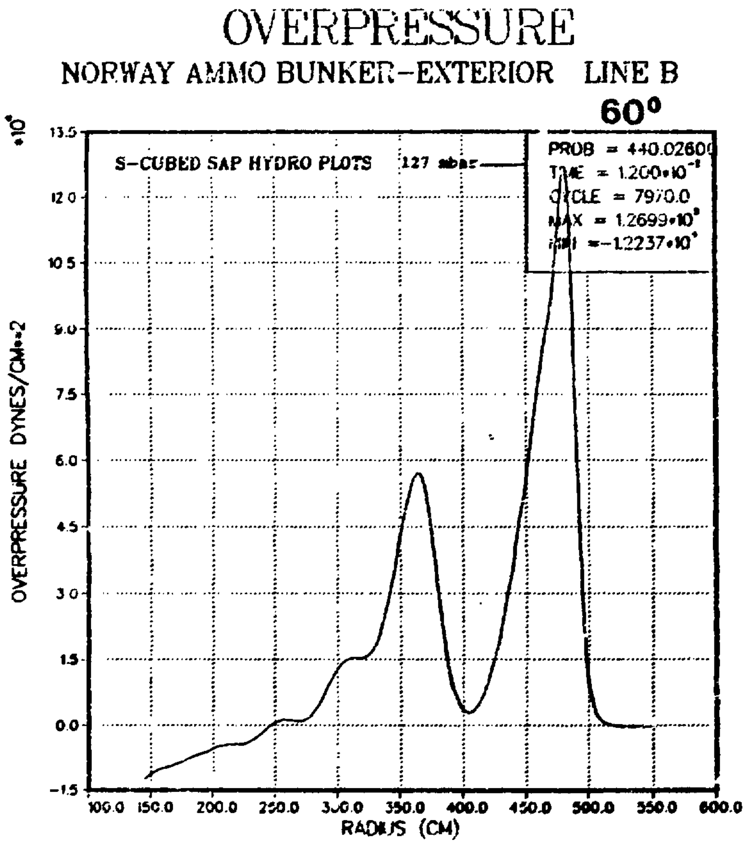


Figure 36. Overpressure versus Range Plot Along 60° Line at 12.00 msec.

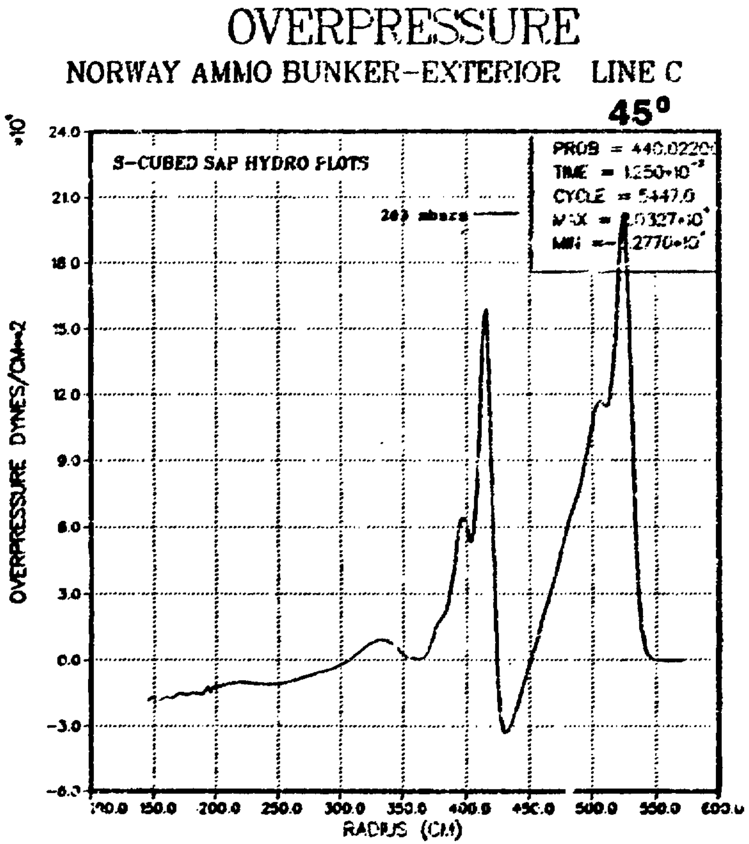


Figure 37. Overpressure versus Range Plot Along 45° Line at 12.50 msec.

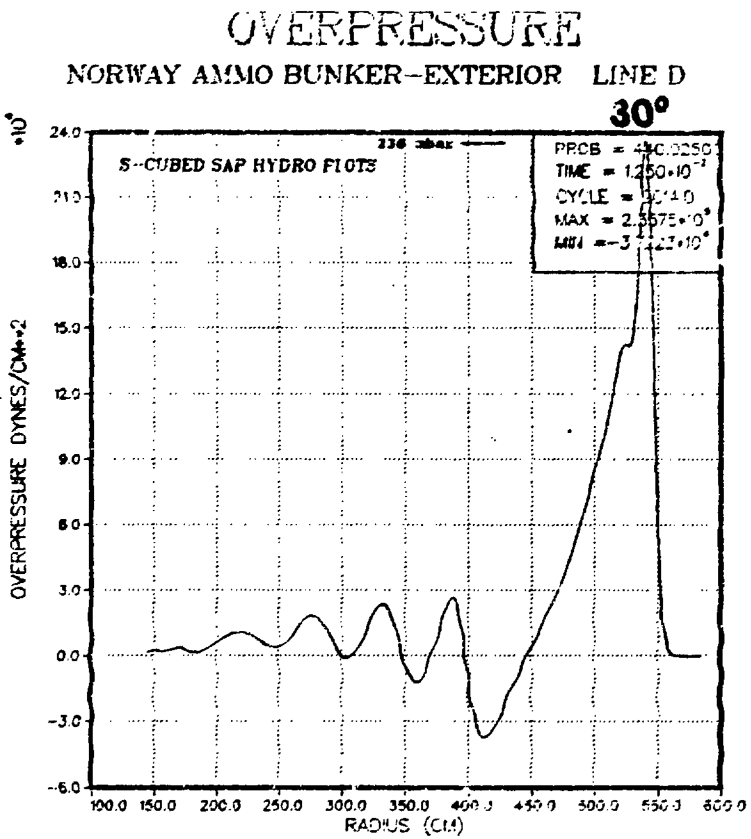


Figure 38. Overpressure versus Range Plot Along 30° Line at 12.50 msec.

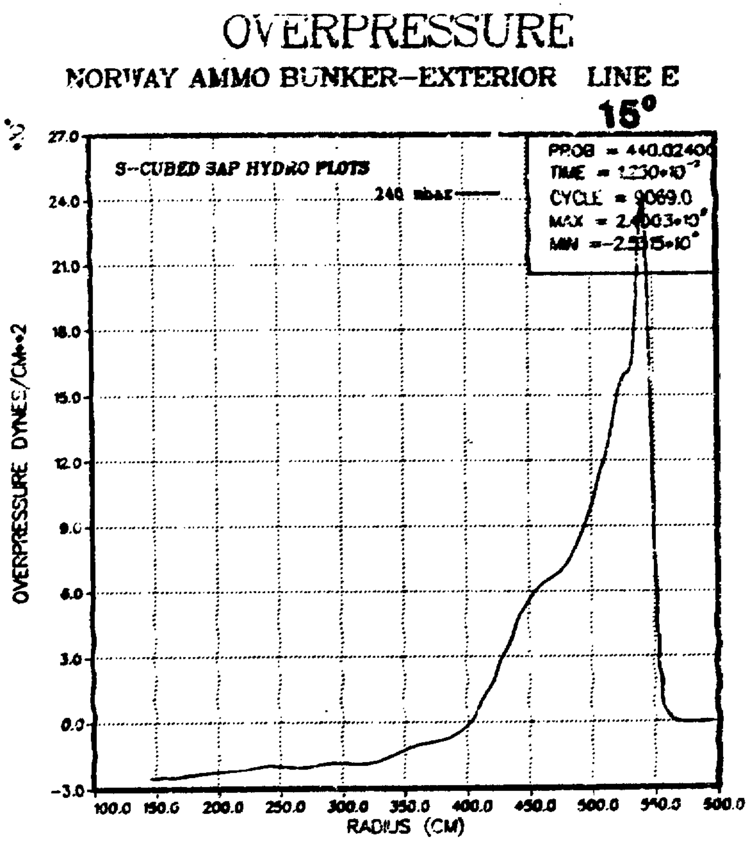


Figure 39. Overpressure versus Range Plot Along 15° Line at 12.50 msec.

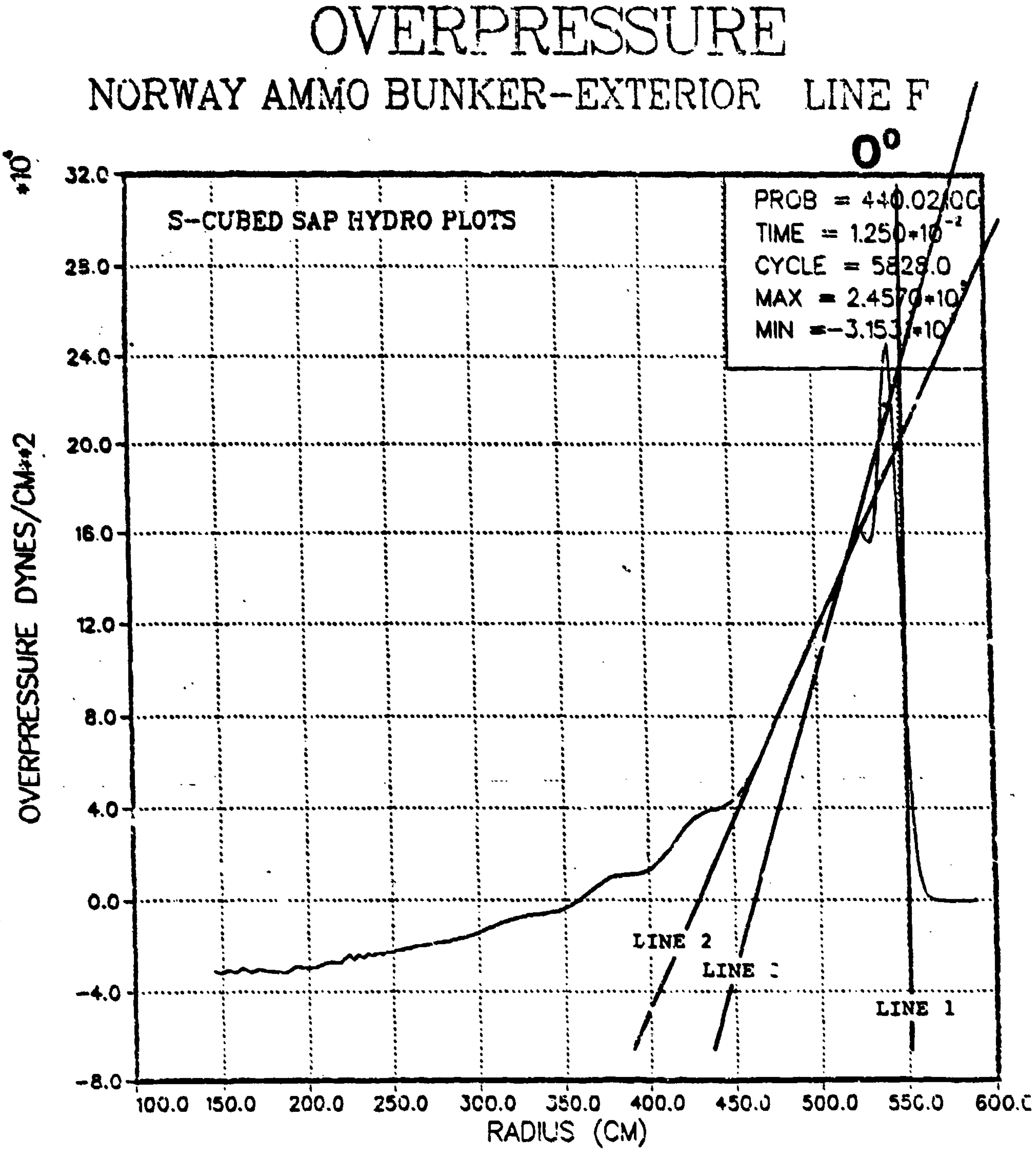


Figure 40. Overpressure versus Range Plot Showing Method of Determining Triangular Wave Input for NLAWS.

the desired level. NLAWS was written at the Air Force Weapons Laboratory and is used to find the peak overpressure and velocity at ranges below approximately 280 mbar (4 psi).

The NLAWS program was run for each of the one-dimensional calculations, beginning at the last time from the SAP calculations of Phase 3. The objective was to determine a range at which the peak overpressure would have attenuated to 50 mbar. Because the input waveform for NLAWS must be triangular, waveforms from the SAP one-dimensional calculations had to be modified. This was done in the following manner. First, a vertical line was drawn through the mid-point of the first rise on the SAP waveform. In Figure 40, this line is designated "LINE 1". Second, a representative slope was chosen on the falling portion on the wave, and a line was drawn tangent to the sloping portion (illustrated by "LINE 2" in Figure 40). These two lines defined a peak overpressure and a positive phase duration for input to NLAWS. Because there was some uncertainty about the choice of the tangent line, a second line (LINE 3) was chosen and a second NLAWS calculation was performed. Choosing the input waveform in this manner eliminates numerical shock-front smearing and any numerical overshoot from the hydrocode results. The two different NLAWS calculations provide an estimate of the accuracy of the results.

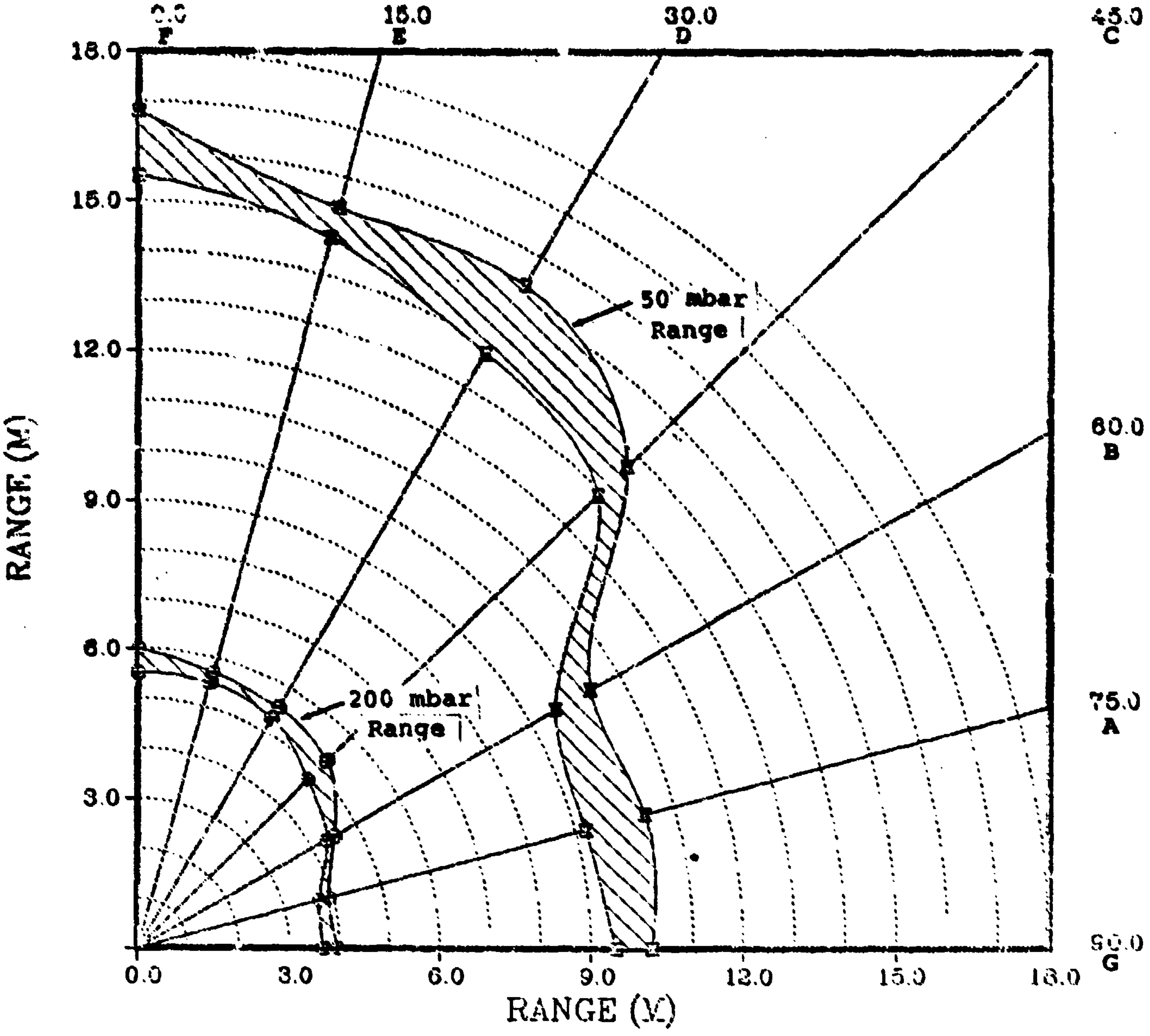
The procedure described previously was applied to each of the seven waveforms from the SAP calculations given in the last section. In cases such as that for the 45 deg line (Figure 37), in which the waveform consisted of two distinct pulses, only the first (and largest) was used. Under acoustic conditions, all parts of a wave propagate at the same speed, thus there is no overtaking of the front-running portions by those following.

VI. CONCLUSIONS

The peak-overpressure versus range listings generated by NLAWS as described in the previous section were interpolated as necessary to determine the range at which this peak falls below 50 mbars. Because two sets of input conditions were defined, a spread in range was obtained at each angle. The results are shown in Figure 41 (outer curve). As can be seen, for positions directly in front of the tunnel entrance (0 deg), a distance of 17 meters is required to assure that the peak overpressure experienced will be less than 50 mbars. For off-axis positions, 16 meters is sufficient at 15 and 30 deg and 14 meters at 45 deg. At angles of 60 deg or greater, only 11 meters is required. For the full-scale situation of interest, in which 2000,000 kgm of explosive are detonated, all distances would be scaled up by a factor of 100.

The inner curve in Figure 41 defines the 200-mbar peak overpressure distances. This curve was determined in exactly the same way as the 50-mbar curve, except that in this case the results were taken from the early part of the NLAWS run or, at several of the angles, directly from the SAP results.

NORWAY AMMO BUNKER-EXTERIOR



OVERPRESSURE CONTOURS

Figure 41. Ranges for 50 and 200 mbar Peak Overpressures as Functions of Angle.

LA-UR-86

TITLE: NEW AIRBLAST CRITERIA FOR MAN

AUTHOR(S):
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John T. Yelverton
E. Royce Fletcher

SUBMITTED TO:
Presented at the Twenty-Second DoD Explosives Safety Seminar, Anaheim Marriott Hotel, Anaheim, CA, 26-28 August 1986.

Sponsored by the Department of Defense Explosives Safety Board, Alexandria, VA 22331-0600.

Los Alamos

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Los Alamos, New Mexico 87545

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NEW AIR BLAST CRITERIA FOR MAN

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INTRODUCTION

The purpose of this report is to present direct-airblast casualty criteria for personnel in the open and in foxholes. The criteria relate the incident blast overpressure required to produce 1-, 50-, and 99-percent incidences of casualties as a function of the overpressure duration. Hopefully, the information presented will contribute to establishing safe limits for personnel.

Injuries from the direct-overpressure effect are usually to the hollow or gas containing organs of the body. The lungs are considered to be the target organ because their disruption by the blast permits air to enter the circulation leading to an early death from coronary and cerebral air embolism. Associated with lung hemorrhage are bloody froth in the upper respiratory tract and an increase in respiratory rate. Contusions in the lining of the gastrointestinal tract and perforations at higher blast levels are common features of direct-blast effects. Hearing loss from eardrum rupture and neurosensory lesions in the inner ear are the more far reaching direct blast effects.

DEFINITIONS OF A CASUALTY

There are several definitions of a casualty. One is death or a person incapable of performing any task. Another is a person reduced to below 50 percent of his undegraded performance level. Still another is percent incapacitation, which relates the percent that the man's performance is degraded. In this report, a casualty is defined as a combat ineffective (CI), a person who can not perform his assigned task at 5 minutes.

Human incapacitation is almost always influenced by subjectivity and by the circumstances of the casualty as well as the severity of the trauma. The only available direct-airblast criteria are based on the severity of the observed injury in animals, and it is necessary to define incapacitating lesions as injuries which, had they occurred in man, would almost certainly produce a casualty. Once the criteria are formulated, one then looks for information from accidental explosions to evaluate them. Unfortunately, well-documented cases of human exposure to blast are rare--that is, the weight of the explosive and the exact distance from the explosion and, also, the explosions usually occur inside structures or it may not all detonate at once.

Recently, the need arose to evaluate existing direct-blast criteria for personnel and, if need be, formulate new ones. Blast criteria have not been scrutinized because for conventional ordnance fragments provide the dominant effect. Because of their very short duration, blast waves of very high overpressures (that occur close-in to the charge) are required for blast injuries. In the case of nuclear blasts, having very long-durations, much lower overpressures can inflict injury. However, other effects usually override direct-blast such as nuclear, thermal, and blast displacement.

Kokanakis at BRL reviewed the state-of-the-art for blast incapacitation and concluded that existing criteria were too stringent, Reference 1. He suggested that the LD_1 lethality curve is too severe a measure of incapacitation and would underestimate casualty production as well as the effectiveness of blast producing weapons. The LD_1 criteria state that fifty percent of the personnel exposed to a one-percent lethal airblast overpressure would become casualties from lung hemorrhage. The lung hemorrhage would be severe enough to produce bloody froth in the trachea, mouth, nose, and increase the respiratory rate. Exertion could be fatal. This LD_1 curve reported by Bowen, Reference 2, was based on the dose-response curves of about a dozen species of animals exposed to blasts of different positive durations from high explosives in the open and in shocktubes. Actually, more than three quarters of the animals given an LD_1 level of blast sustain severe lung injury.

Kokanakis proposed relating the blast overpressure required to produce threshold lung injury to 99 percent incapacitation (defined as the percent degradation in performance). He also proposed blast overpressures for a 50-percent incidence of eardrum rupture as the threshold for incapacitation, Figure 1.

For our purposes, we did not consider threshold lung injury as incapacitating. At threshold levels, the lesions consist of petechial hemorrhages (pinhead sized) which we find have no affect on respiration or blood gas concentrations. Although eardrum rupture may result in hearing loss and, thus, correspond to a casualty by definition (unable to hear), we would only consider severe ear injury as possibly casualty producing, i.e., eardrum completely destroyed and disruption of the ossicular chain that occur at the higher overpressures.

ONE-HALF LD_{50} CRITERIA

The newly proposed direct blast criteria relate a 50-percent incidence of combat ineffectives (CI) to one-half the LD_{50} blast level reported by Bowen, Reference 2. It assumes that 50 percent of the personnel exposed to $LD_{50}/2$ airblasts would become CI from lung hemorrhage. A review of pertinent blast-dose response data from animals supports this assumption. There was sufficient lung damage to increase the lung weight, produce bloody froth in the upper respiratory tract, and increase the respiratory rate. At $LD_{50}/2$ blast levels, the animals also sustained contusions of the gastrointestinal tract and ear injury of a severe form in about half the cases. A 99-percent incidence of CI was set at the LD_1 level and the 1-percent CI level was found by extrapolation downward using the average slope taken from the animal dose-response curves. The $LD_{50}/2$ blast curve is about 30 percent lower than the LD_1 curve and about twice the lung threshold curve.

Figures 2, 3, and 4 present the percent-CI curves as a function of maximum incident overpressure and duration of the positive pulse. Basically, the curves are those from Bowen, Reference 2, with the 50- and 1-percent CI curves added. Figure 2 applies to man standing or prone broadside to the blast wherein the dynamic pressure was added to the incident side-on overpressure. Figure 3 gives the percent-CI curves applicable to man prone end-on to the blast where the incident overpressure alone represents the airblast dose. Figure 4 shows the incident blast overpressure required for the indicated percent CI for personnel against or close to a reflecting surface oriented normal to the wave. In this instance, the reflected overpressure represents the airblast dose. Over the 1- to 10-msec duration range, the incident overpressure associated with CI_{50} decreases by a little over a factor of 3 for the broadside and reflecting geometries of exposure. Over the same span of durations, the CI_{50} for the end-on situation drops by a factor of 5. All these curves apply to blast waves that have the maximum overpressure at the leading edge of the wave. They should be used with reservations to estimate man's response to more complex blast waves that occur within enclosures.

The threshold lung injury curve in the figure was set at one-fifth the LD_{50} and was based on the aforementioned interspecies studies. As already mentioned, the threshold lung injury was a trivial lesion. However, at overpressure levels required for this lesion, one would expect a high probability of ear injury.

DIRECT BLAST CRITERIA FOR PERSONNEL IN FOXHOLES

Curves showing the incident overpressures necessary to produce 1-, 50-, and 99-percent CI for personnel crouching in foxholes as a function of the duration of the incident wave is presented in Figure 5. The curves apply to a standard two-man open foxhole (2x6x4.5 ft deep) oriented side-on to the blast. These curves are based on the data points showing the response of animals exposed to blast in the standard foxhole or ones of comparable geometries. The datum point for man was estimated for long-duration waves, Reference 3. Data points for sheep in the standard foxhole were obtained with 64-lb and 1-ton charges, Reference 4. Those for goats in open trenches side-on were from a test using 0.75 tons, Reference 5. The other datum point for goats, at 100 msec-duration, was obtained on a 100-ton shot with subjects in the open portion of a half-covered foxhole, Reference 6. Dogs were in the standard foxhole side-on to the blast from a 40-kt shot, Reference 7. The 50-percent CI curve was first established from this data and then the 99-percent and 1-percent CI curves were drawn 30 percent above and below it. The 99-percent CI curve is equivalent to an LD_1 curve.

In the side-on orientation, this foxhole affords more protection from the blast than when it is end-on. Little protection is provided to the occupants when the incident shock has a high angle of incidence. A crouching position is better than prone because the highest overpressures occur at the bottom of the foxhole.

DISCUSSION

A review of the published and unpublished information on animal response to an airblast indicates the $LD_{50}/2$ direct airblast criteria is sound. Data for sheep exposed to airblasts of short duration (3-5 msec), Reference 8, intermediate durations (15 msec), Reference 9, and dogs given long-duration blasts (400 msec), Reference 10, all support the proposed criteria. A well-documented case of human exposure to the accidental detonation of a 3.5-lb uncased charge indicates that casualty predictions by the criteria are assured, Reference 11.

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LIST OF ILLUSTRATIONS

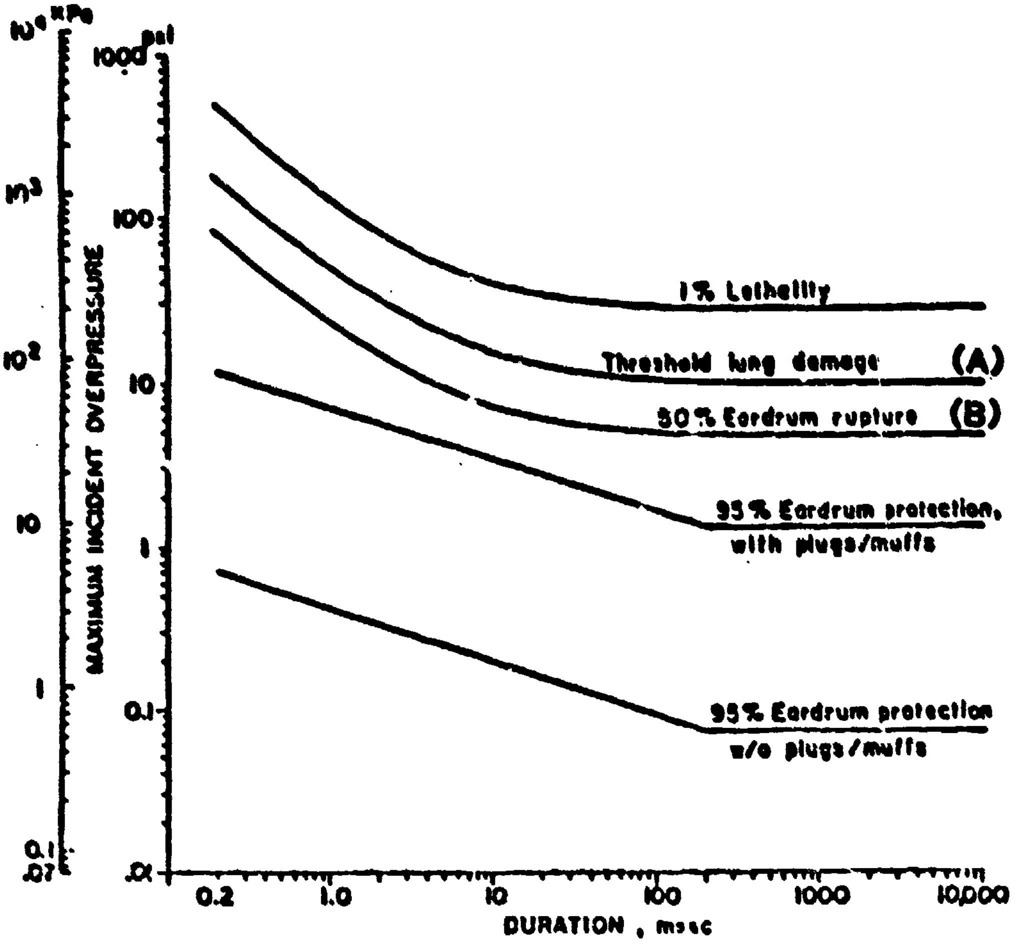

Figure 1. Lethality and Damage/Injury Curves Predicted for a 70-lb Man Applicable to the Freestream Situation (from Ref. 1). The "A" curve indicates 99% incapacitation and the "B" indicates the threshold for incapacitation.

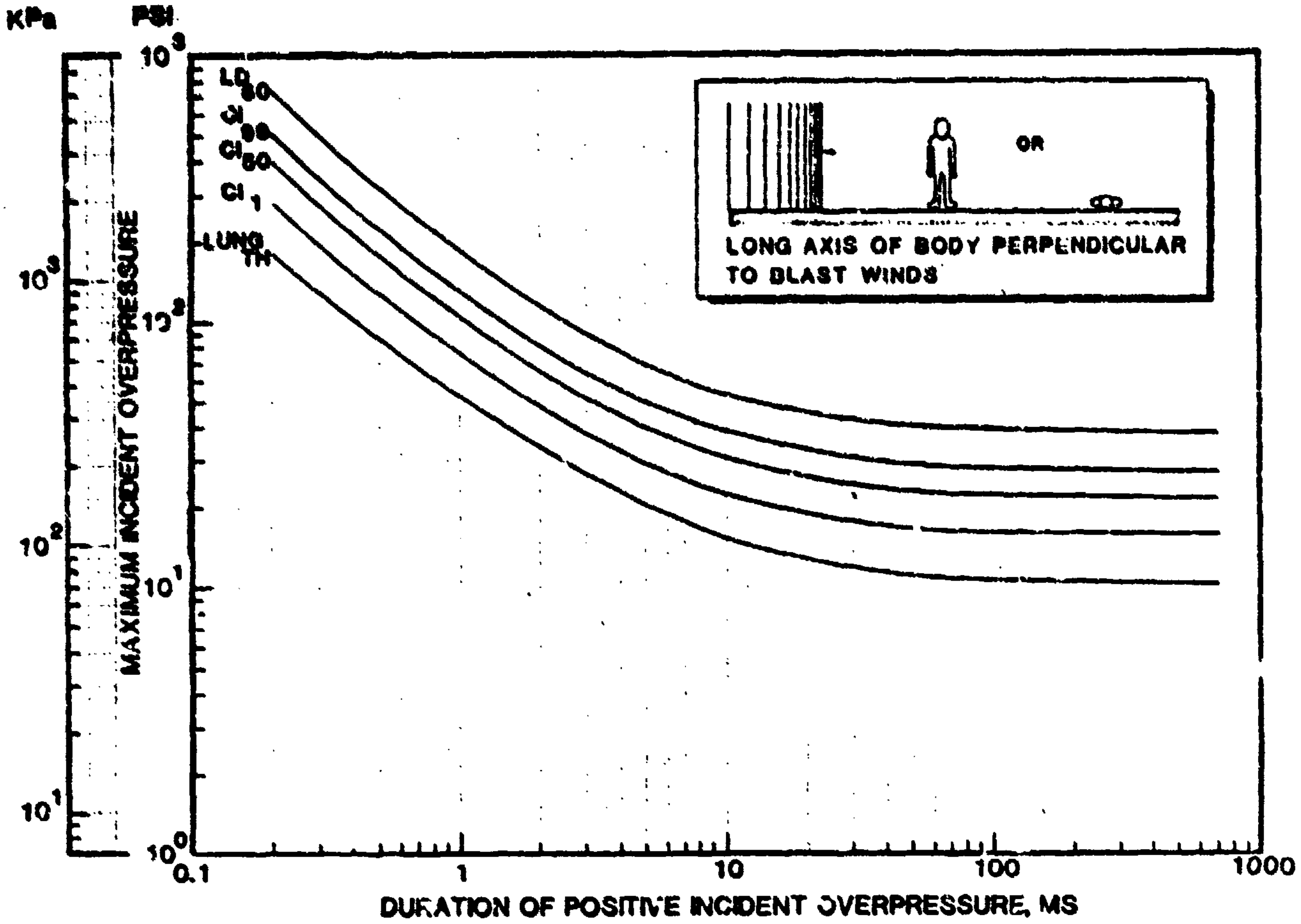

Figure 2. Direct Blast Casualty Criteria Predicted for Man Where the Long Axis of the Body is Perpendicular to the Direction of the Blast.

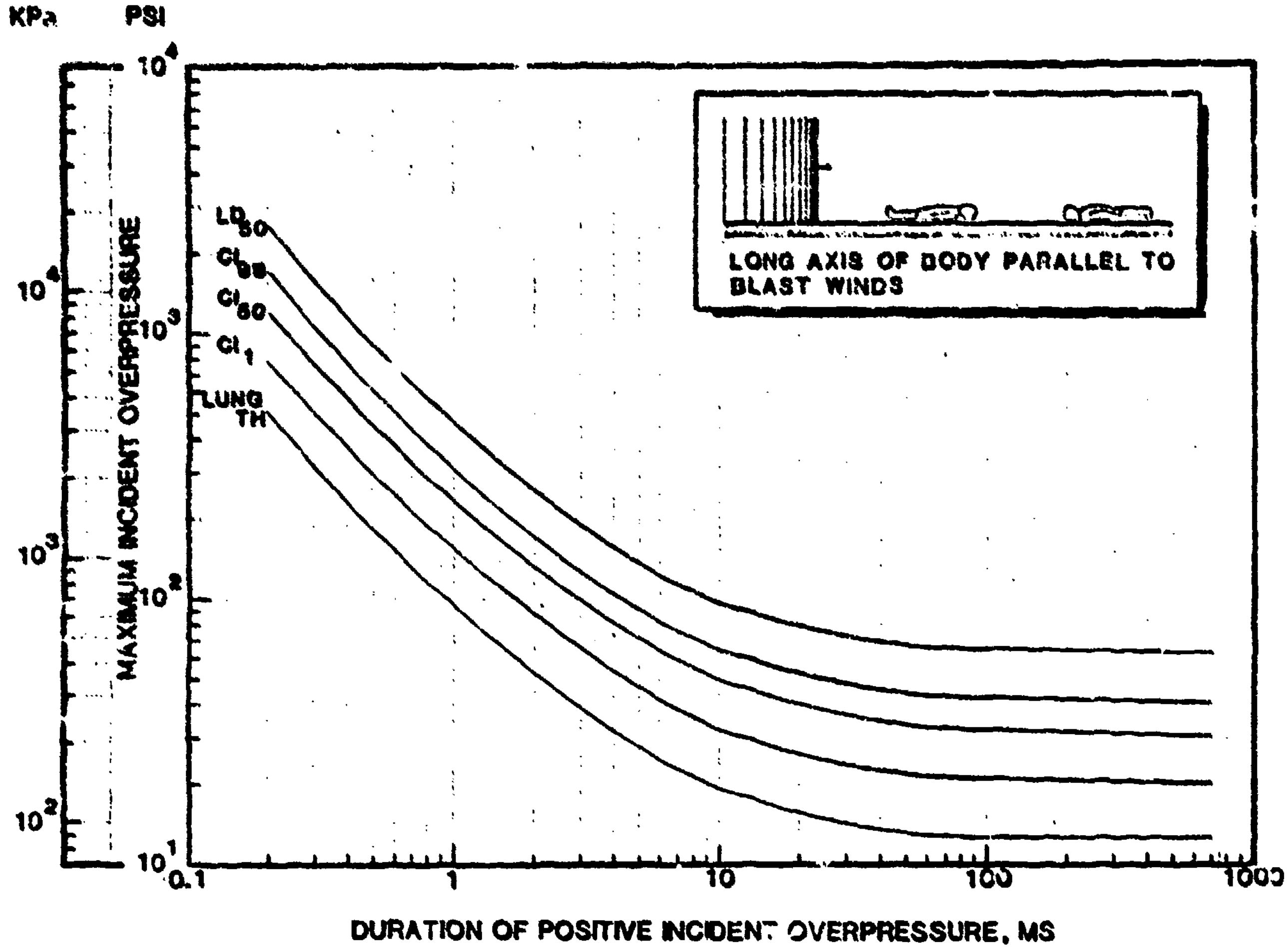

Figure 3. Direct Blast Casualty Criteria Predicted for Man Where the Long Axis of the Body is Parallel to the Direction of the Blast.

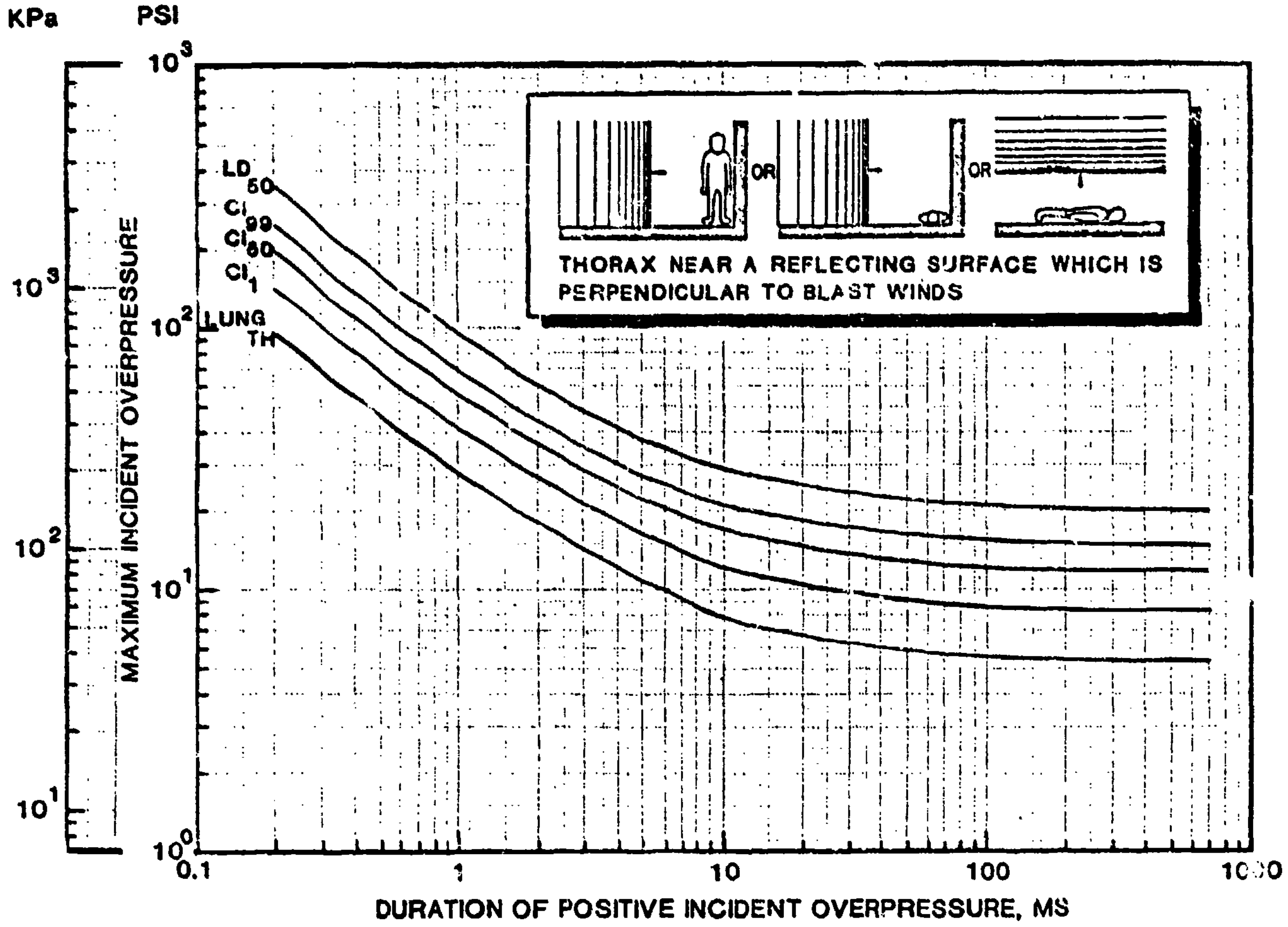

Figure 4. Direct Blast Casualty Criteria Predicted for Man Where the Body is Against a Reflecting Surface Perpendicular to the Incident Wave.

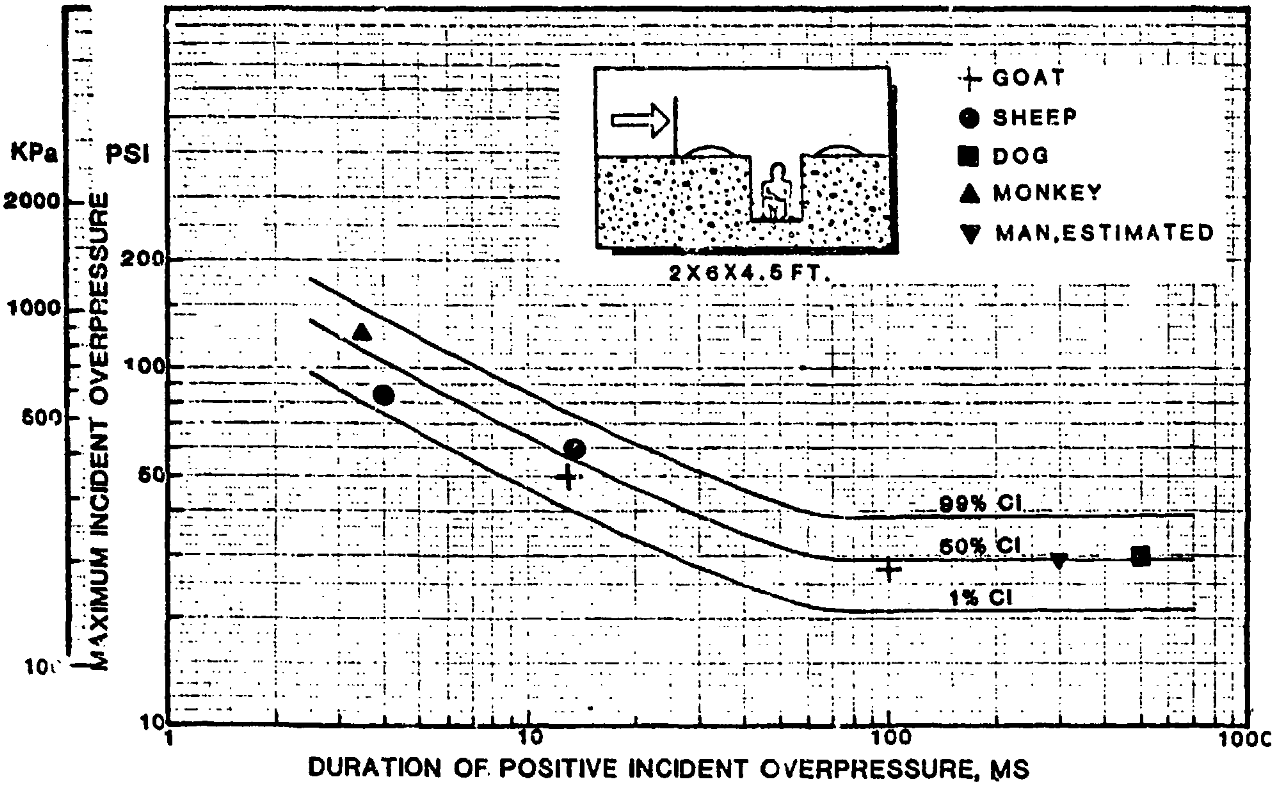

Figure 5. Direct Blast Casualty Criteria Predicted for Man in an Open Two-Man Foxhole (2x6x4.5 ft) Side-On to the Blast.

FIELD TEST TO VERIFY
THE
COBURN - FORSTER - KANE
EQUATION

PRESENTED

AT THE

22nd DOD EXPLOSIVES SAFETY SEMINAR

26 - 28 AUGUST 1986

AT

ANAHEIM MARRIOTT HOTEL
ANAHEIM, CALIFORNIA

BY

MARTIN MOSSA

SYSTEM SAFETY ENGINEER

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U.S. ARMY COMBAT SYSTEMS TEST ACTIVITY
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FIELD TEST TO VERIFY THE COBURN - FORSTER - KANE EQUATION

1. BACKGROUND

Toxic gas tests of weapons when fired from vehicles are part of the mission of the U.S. Army Combat Systems Test Activity (USACSTA) at Aberdeen Proving Ground (APG), MD. The results of these tests are usually included in the safety evaluation of a new or modified system, weapon, or round of ammunition.

At APG, four primary toxic gas compounds are measured during weapons firings from vehicles including carbon monoxide (CO), nitrogen dioxide (NO_2), ammonia (NH_3), and sulphur dioxide (SO_2). The principal toxicant threatening operating crews is CO. The gas is odorless, colorless, and tasteless. Episodic CO exposures which may be tolerable from health and safety viewpoints may actually be threatening to health and/or mission accomplishment (performance considerations) when these exposures occur repeatedly. Simply stated, the explanation is that CO has an affinity for blood hemoglobin such that it combines with it very rapidly but is extremely slow in being eliminated from the blood by the body. Accordingly, the net effect is that CO reduces the oxygen carrying capacity of the blood which can result ultimately in health and performance impairment or even death as a function of the numerous factors affecting the severity of the exposure(s).

Coburn-Forster-Kane (C-F-K) Equation: During 1976, the U.S. Army Human Engineering Laboratory ~~(USAHEL)~~ undertock a critical examination of the standards and methods used by the Army for evaluating human exposure to gaseous CO which results primarily from firing weapons from enclosed combat vehicles. Both transient and steady-state exposures were considered during the study of this issue, but the brief, high-level transient type exposure, typical of most combat situations, was of principal interest. As a direct result of that study and subsequent coordination with various activities of the U.S. Army Surgeon General (SG), the materiel development community, ~~U.S. Army~~ Training and Doctrine Command (USATRADOC) and USATECOM, the CO exposure standards of MIL-STD-1472 and the evaluative procedures of MIL-HDBK-759A were adopted by the military services to reflect a more realistic approach to the issue of CO exposure than was applied previously. The new evaluative procedure involved the prediction of blood carboxyhemoglobin (COHb) levels in exposed soldiers by using an empirical equation developed by researchers more than a decade earlier. The predictive technique involves the knowledge of CO exposure level, its time duration and the level of physical exertion of the exposed person during and following exposure transients typical of training or battle scenarios. Because the standards and evaluative procedures governing CO exposure adopted in 1981 were based exclusively upon laboratory research with humans, both were considered as interim and subject to periodic revision whenever justified by data obtained through either continuing laboratory research or substantiation of changes to the C-F-K algorithm constants through actual field trials in realistic environments.

Some evidence suggested that the C-F-K equation (published in modified form in MIL-HDBK-759A) was overpredicting COHb blood levels significantly: (a) occupational medicine residency project; (b) unpublished data gathered by the Defence and Civil Institute of Environmental Medicine (DCIEM-Canada), and

(c) review meetings/ discussion among specialists representing USAEHA, Medical Research and Development Command, and DCIEM (Canada). Two actions resulted from the existing evidence and dicussions:

a. The empirical constants of the C-F-K algorithm were revised to correct a fundamental error in the units and the equation was revised as follows:

$$\% \, COHb_t = \% \, COHb_0 \, [\exp(-t/A)] + 218 \, [1 - \exp(-t/A)] \, [1/B + ppmCO/1403] \quad (1)$$

where

Work Effort Scale	Work Effect Description	A Value	B Value
1	Sedentary	425	806
2		241	1421
3	Light Work	175	1958
4		134	2553
5	Heavy Work	109	3144

b. A field test protocol was drafted, approved, and implemented (app A), which had the principal goal of verifying the predictive quality of the C-F-K equation as used in the evaluations. This report presents the major findings of the field trials completed during June and July 1985. The individuals' participation were completely voluntary as outlined in the protocol. All participants were attached to the Military Support Division, U.S. Army Combat Systems Test Activity, Aberdeen Proving Ground, Md.

2. OBJECTIVES

This research is categorized as a group of field experiments which, for this study, used a safety certified M60A3 tank. As previously indicated, the research is intended to provide sufficient data to:

a. Verify that the modified C-F-K equation, as used currently, is overpredicting the percent COHb blood levels of ground combat vehicle crews exposed to CO emissions resulting from weapons fire.

b. Assuming that the hypothesis is confirmed by the test results, modify the C-F-K equation, published in MIL-HDBK-759A to predict COHb blood levels of crewmen conservatively, accurately, reliably, consistently, and realistically.

3. SUMMARY OF PROCEDURES

a. Safety Procedures. Standard Operating Procedures (SOPs) and Test Operating Procedures (TOPs) were used during this test. Procedures pertaining to the volunteers participating in the study were controlled by the USACSTA Field Test Protocol (app A) which was approved by the Department of the Army, Office of the Surgeon General, Human Use Review Office (app A).

b. The policies and procedures of AR 70-25 governing the use of volunteers as subjects in Department of the Army (DA) research applied to the protocol for this study only in the following manner. The subjects were biologically monitored/supervised by a physician who also obtained blood samples at required intervals during the test. The vehicle/equipment used in the test had previously been safety-certified and the participants were not experimental subjects in the context of AR 70-25. The M60A3 tank was selected as a test bed (fig. 1.3-1) for this investigation. The results of this test are independent of prior toxic gas tests performed on this vehicle and/or weapon system.

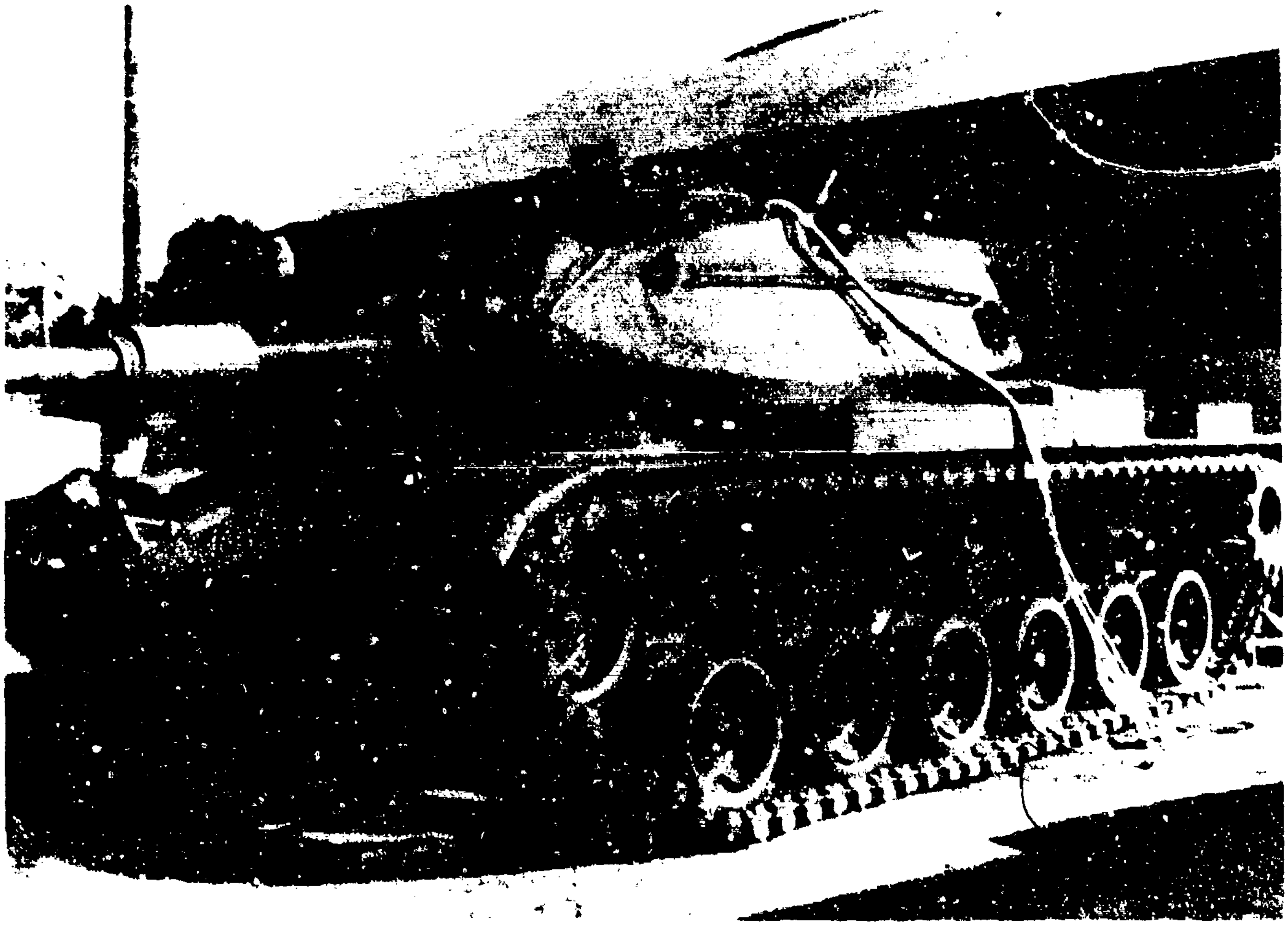


Figure 1.3-1. M60A3 test bed.

The 38 participants were encouraged to ask questions of the principal investigators or the medical surveillance officer on all matters pertaining to test procedures and equipment. Each participant was informed of the results of monitoring and its significance. Appropriate entries were made in the health records of each participant and all data collected for each individual was treated with confidence. This test was supported under contract by The Johns Hopkins University, Center for Occupational and Environmental Health.

c. Test Procedure: Prior to arriving at the test site, the participants were divided into tank crews of three individuals: loader, gunner, and commander. The only restriction placed on the crew selection was that the loader had to be a qualified tanker and familiar with the M60A3 system and the M240 coax machinegun. This was necessary because the individual in this crew position was required to operate the machinegun and the tank's main armament weapon system (fig. 1.3-2). Each individual was briefed as to the importance, objectives, procedures, and potential benefits of the test. All participants were volunteers who completed and signed a Volunteer Agreement Form and a Consent Explanation Form (app A) along with a demographic questionnaire. Physical examinations were given to each crew member at the U.S. Kirk Army Health Clinic (USKAHC) located at APG.

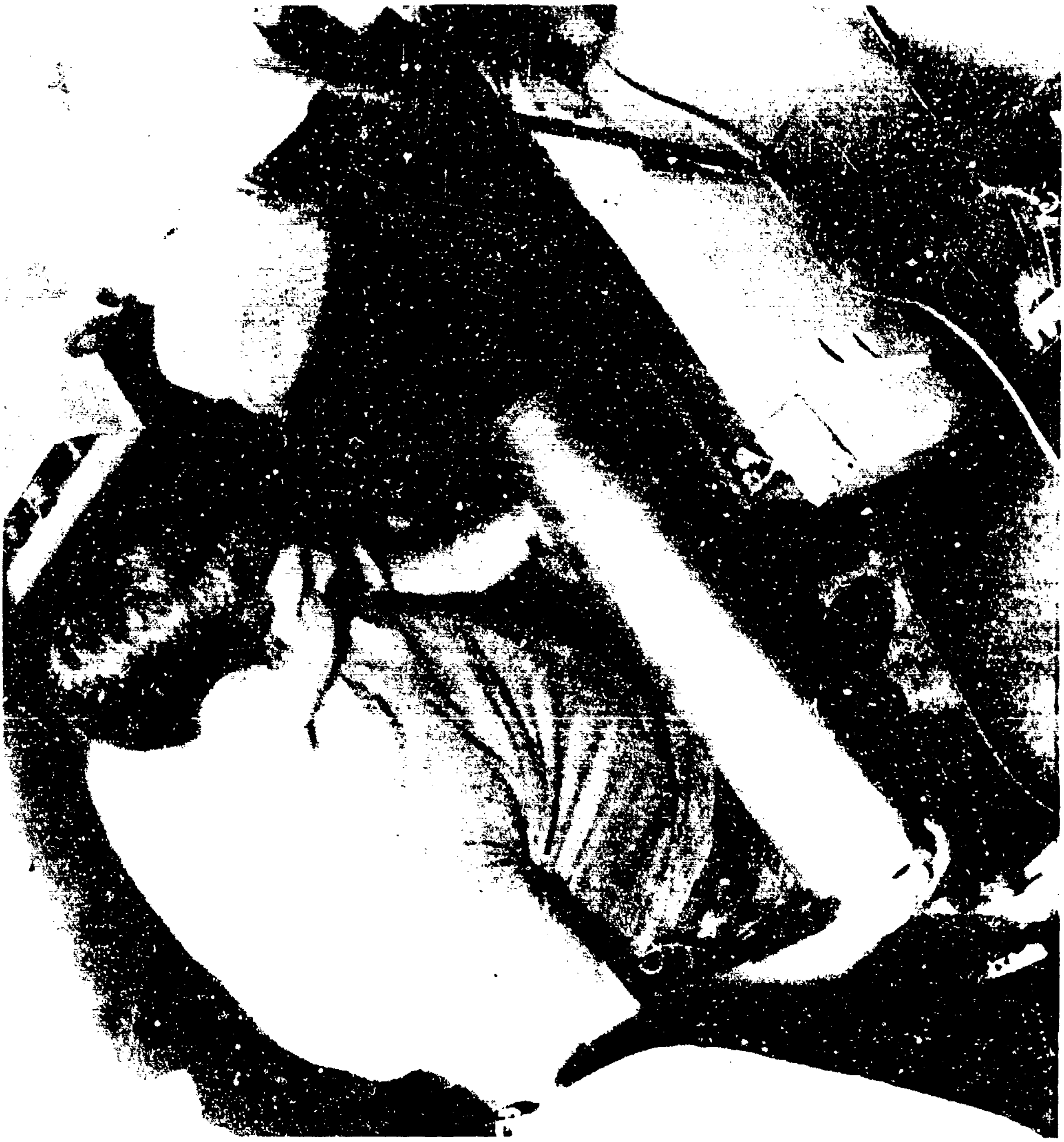


Figure 1.3-2. Loader chambering the dummy 105-mm HEAT round.

Two firing sequences per day were conducted (fig. 1.3-3): one in the morning and one in the afternoon. Calibration bursts were fired by civilian personnel prior to each test trial to verify burst length, time of exposure expected, and CO concentration. When each tank crew arrived at the site, a spirometry test (fig. 1.3-4) was performed as was a helium dilution lung volume test. Blood pressure and pulse were recorded and COHb was determined with a co-oximeter (fig. 1.3-6) at the site from drawn blood samples (fig. 1.3-5), and two alveolar air samples (fig. 1.3-7) were taken.

Figure 1.3-3. Participant entering the M60A3 tank for a firing sequence.

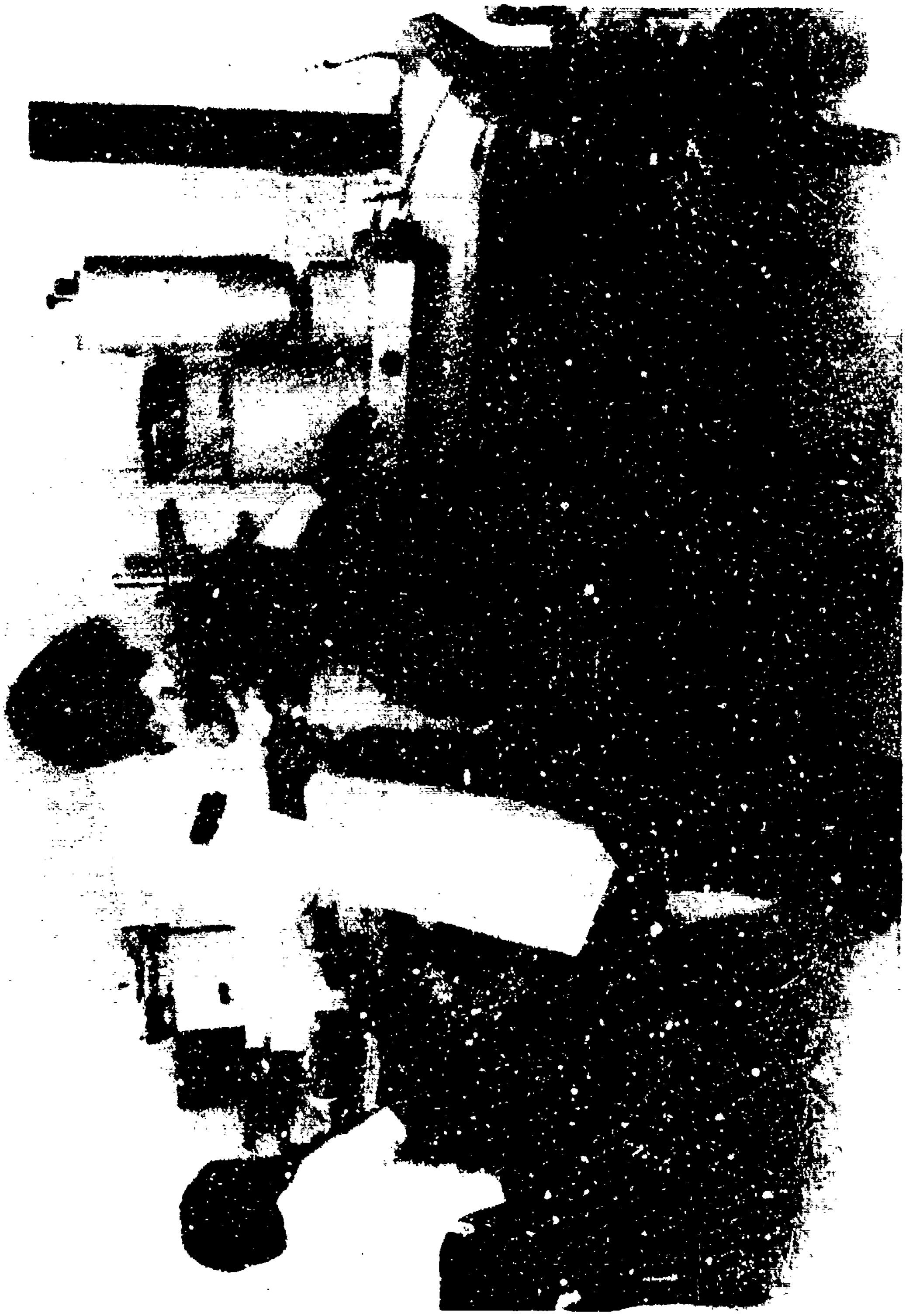


Figure 1.3-4. Spirometry Test.

Figure 1.3-5. Blood samples being drawn from participant.

Figure 1.3-6. On-site blood co-oximeter for COHb levels.

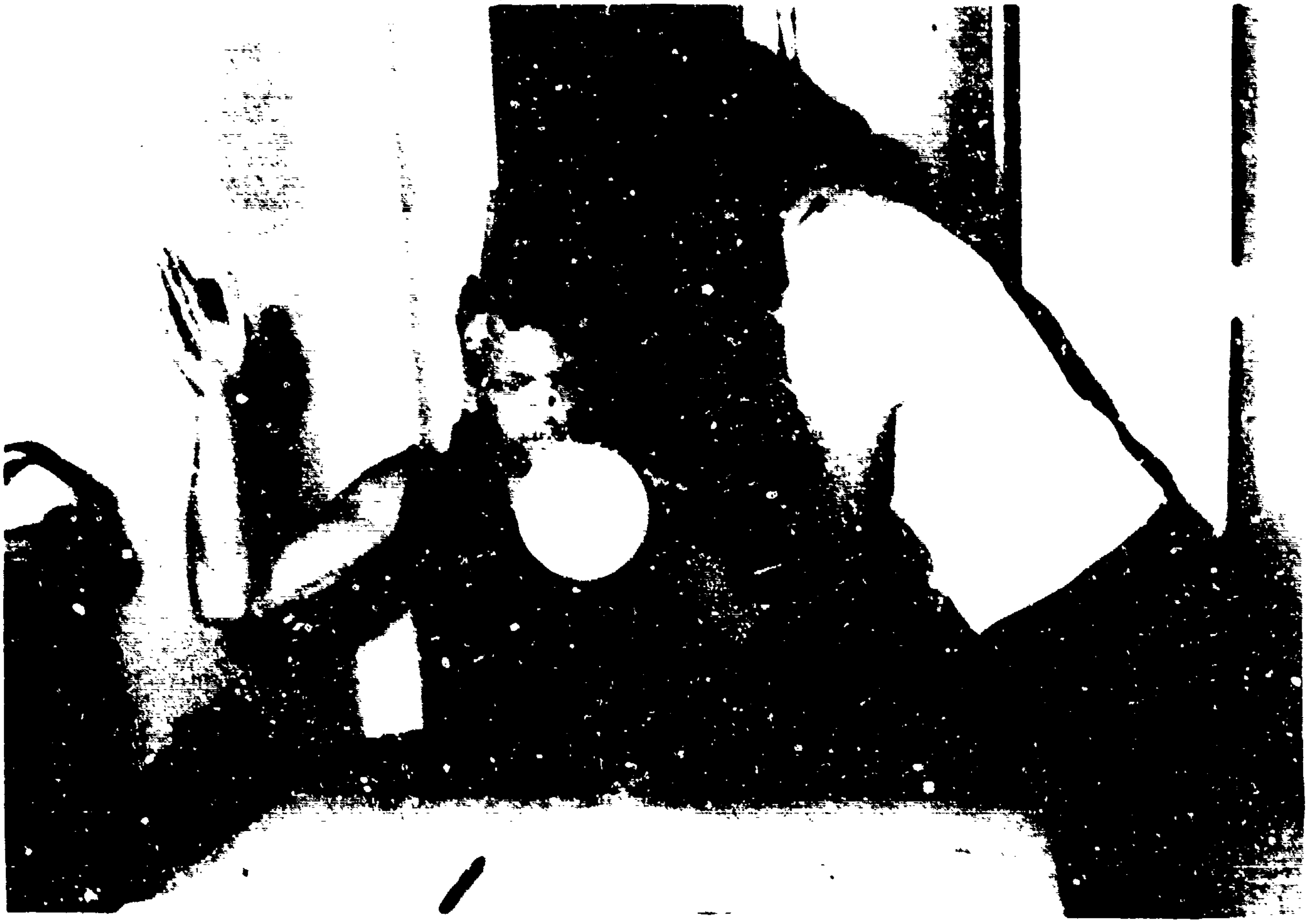


Figure 1.3-7. On-site alveolar sample to measure COHb.

CO concentrations inside the tank were monitored continuously using the instruments contained in a van (fig. 1.3-8). Prior to each trial, the ammunition ready box for the M240 machinegun was loaded with the required quantity of rounds. When the prefiring measurements and checks were completed and the CO concentration in the tank was zero, the crew entered the tank, and all hatches were shut. The loader then fired the complement of ammunition (fig. 1.3-9) in short bursts of five rounds every 3 or 4 seconds. When the ammunition was expended, the loader chambered and extracted a full weight dummy 105-mm high explosive antitank (HEAT) round five times to simulate the physical effort during a firing episode. At the end of this exercise, the crew was sedentary until the end of the test period. Data acquisition began when the first round was fired and continued until the ventilation blower was turned on at the conclusion of the test trial. All hatches were then opened. The tank crew was in constant communication with USACSTA personnel in the instrumentation van and outside the test vehicle during the test trial. The latch on the small ballistic cover in the larger loader's hatch had been modified so that it would close securely but the cover was operable from the outside. This feature permitted personnel outside the vehicle to extend one hand inside and open the loader's hatch in an emergency.

Figure 1.3-8. Instruments mounted in instrumentation van.

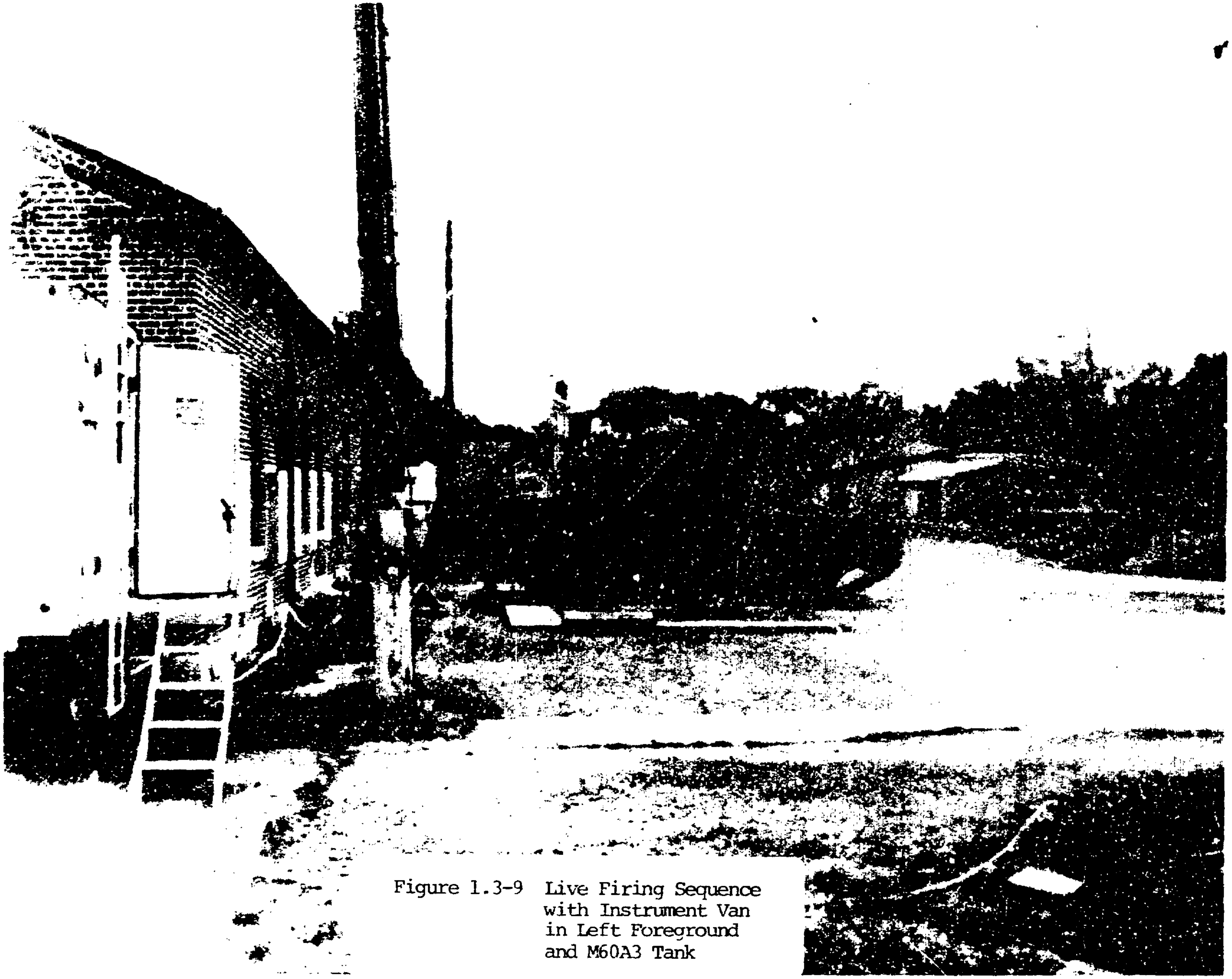


Figure 1.3-9 Live Firing Sequence with Instrument Van in Left Foreground and M60A3 Tank

4. ANALYSIS

a. Demographic and Physiologic Data Analysis

The average soldier in this study was a young (mean age 22.8) male smoker (66%) averaging 69.8 inches tall and weighing 177.6 pounds. The mean pretest COHb and alveolar CO were 3.6% and 17 ppm respectively. The smokers averaged about 17 cigarettes per day with the last cigarette smoked about 50 minutes prior to the test exposure. The mean initial COHb level for the smokers (n = 25) was 4.6% (SD = 2.0) and the mean for nonsmokers (n = 13) was 1.6% (SD = 0.4). The % COHb ranges for each group were 1.2 to 2.5 and 1.2 to 8.6, respectively.

b. COHb Level Prediction Using the C-F-K Equation

(1) Revised modified equation.

(a) The most recent version of the equation currently used by the Army is the revised version released for field use in February 1985. This equation has been included in the latest revision of MIL-HDBK-759.

(b) As a result of the demographic and pretest physical data, it was discovered that the average initial COHb level for the population was 3.6%. Furthermore, the lowest level measured was 1.2%. The initial % COHb value to be used for predicting COHb blood levels should be addressed as an issue for future study. For the purpose of this analysis, the actual measured initial CoHb was used to predict final COHb levels for each soldier. The average CO levels (table 1.5-1) were used for the calculations.

(2) Revised modified equation versus modified C-F-K equation (MIL-STD-759A). The predicted rise in COHb levels from each of the two equations were compared at work effort levels 2, 3, and 4. It was found that the modified equation predicts significantly higher levels than the revised equation. This verifies the hypothesis that the modified C-F-K equation overpredicted.

(3) Initial % COHb value used in the C-F-K equation. MIL-STD-1472C states that an initial COHb value of 1% shall be assumed for all estimates while using the C-F-K equation to predict final COHb levels. The data presented in this study, which is based on a population sample of 38 male soldiers, indicates that the 1% value is not a reasonable estimate. The average pretest % COHb level for the whole population was 3.6% (SD = 2.2%). The pretest level for nonsmokers was 1.6% (SD = 0.4%) and 4.6% (SD = 2.0) for smokers.

Accordingly, a linear regression analysis was performed to compare the predicted % COHb levels, using the revised equation with $COHb_0 = 1$ and work effort level 4, with the actual % COHb levels. The slope of the plot is 1.16 with a correlation of 0.746. This is further assurance that the predictive equation, as presently used, is overpredicting actual measured values significantly.

(4) Comparison of the rise in COHb between the loader position and the commander gunner positions. Figure 1.5-1 isolates the data for the loader and commander. The revised equation was used for this plot. Due to the location of the loader, in the tank, in relation to the commander and gunner, the loader was exposed to lower CO concentrations than the other two positions. However, based on the available data, the trend is for the equation to overestimate the levels of COHb for sedentary persons while underestimating lower levels for working persons. It would seem then that a greater emphasis for persons physically stressed should be applied in any evaluations involving prediction of COHb levels.

Figures 1.5-2, -3, -4, are graphs which compare the rise in COHb of the predicted levels versus the actual measured levels. The revised equation at work effort levels 2, 3, and 4 was used to plot these graphs. Table 1.5-2 shows the slopes and standard deviations associated with these plots.

TABLE 1.5-1. SUMMARY OF RESULTS

Rd Fired	Trial No.	Pos	Smoker	Avg CO, Corr	Exp Time, min	Pre-blood COHb	Post-blood COHb	Measured DCOHb	Predicted COHb2 Pre-blood	DCOHb2 Pre-blood	Predicted COHb3 Pre-blood	DCOHb3 Pre-blood	Predicted COHb4 Pre-blood	DCOHb4 Pre-blood	Predicted COHbTA $COHb_o$=1
100	1C	Cdr	N	245	4.4	1.3	2.5	1.2	2.0	0.7	2.2	0.9	2.5	1.2	2.2
100	1G	Gnr	Y	433	4.9	2.9	3.7	0.8	4.2	1.4	4.7	1.9	5.2	2.4	3.4
100	1L	Ldr	N	153	4.9	1.6	2.0	0.4	2.1	0.5	2.2	0.7	2.4	0.9	1.8
100	2C	Cdr	Y	471	4.7	8.0	7.9	-0.1	9.3	1.4	9.7	1.7	10.3	2.3	3.5
100	2G	Gnr	N	274	5.1	1.5	2.3	0.8	2.4	0.9	2.7	1.2	3.0	1.6	2.6
100	2L	Ldr	N	125	5.1	1.2	2.5	1.3	1.6	0.4	1.7	0.6	1.9	0.7	1.7
250	3C	Cdr	Y	680	4.8	2.7	4.8	2.1	4.7	2.1	5.5	2.9	6.3	3.7	4.7
250	3G	Gnr	Y	731	5.2	4.1	5.4	1.3	6.4	2.4	7.3	3.3	8.3	4.3	5.3
250	3L	Ldr	N	300	4.8	1.8	4.1	2.3	2.7	0.9	3.0	1.3	3.4	1.6	2.6
250	4C	Cdr	Y	936	4.9	5.6	7.8	2.2	8.4	2.8	9.5	4.0	10.6	5.0	6.3
250	4G	Gnr	Y	846	5.2	5.1	6.2	1.1	7.8	2.8	8.8	3.7	9.9	4.8	6.0
250	4L	Ldr	Y	209	4.9	3.0	5.1	2.1	3.6	0.6	3.8	0.9	4.1	1.2	2.2
250	5C	Cdr	Y	779	6.6	5.5	9.0	3.5	8.6	3.1	9.8	4.3	11.1	5.6	6.8
250	5G	Gnr	Y	579	7.2	4.9	6.1	1.2	7.4	2.5	8.3	3.4	9.4	4.5	5.7
250	5L	Ldr	N	238	6.7	1.3	4.1	2.8	2.3	1.0	2.6	1.4	3.0	1.8	2.8
250	6C	Cdr	Y	919	6.9	7.7	9.8	2.1	11.5	3.8	12.9	5.2	14.5	6.8	8.2
250	6G	Gnr	Y	581	7.1	5.8	7.0	1.2	8.3	2.6	9.2	3.4	10.2	4.4	5.7
250	6L	Ldr	N	358	6.1	1.3	5.0	3.7	2.7	1.4	3.2	1.9	3.7	2.5	3.5
350	7C	Cdr	N	729	6.6	2.0	4.6	2.6	5.0	3.0	6.1	4.2	7.4	5.4	6.5
350	7G	Gnr	Y	771	7.2	3.8	5.3	1.5	7.2	3.5	8.5	4.8	9.9	6.1	7.3
350	7L	Ldr	N	348	7.1	1.7	4.6	2.9	3.2	1.5	3.8	2.2	4.4	2.8	3.8
400	8C	Cdr	Y	769	14.6	8.6	12.0	3.4	15.1	6.5	17.5	8.9	20.1	11.5	13.3
400	8G	Gnr	Y	738	15.2	5.7	9.5	3.8	12.4	6.7	14.8	9.1	17.4	11.7	13.0
400	8L	Ldr	Y	478	14.8	5.5	10.7	5.2	9.6	4.4	11.1	5.6	12.7	7.2	8.8
400	9C	Cdr	Y	1172	11.6	7.0	11.5	4.5	15.2	8.2	18.2	11.2	16.1	8.1	21.5
400	9G	Gnr	Y	764	12.1	5.2	7.4	2.2	10.8	5.6	12.8	7.6	11.3	6.1	15.0
400	9L	Ldr	Y	484	11.9	3.2	7.1	3.9	6.7	3.5	7.9	4.7	7.4	4.2	9.3
400	10C	Cdr	Y	1231	11.7	1.9	8.7	6.8	10.9	9.1	14.2	12.3	17.0	15.1	17.7
400	10G	Gnr	Y	598	12.4	1.2	6.4	5.2	5.8	4.7	7.5	6.4	9.2	8.0	9.3
400	10L	Ldr	Y	450	12.3	4.1	9.3	5.2	7.4	3.3	8.6	4.5	7.1	3.0	9.9
400	12C	Cdr	N	783	11.9	1.4	6.1	4.7	7.3	5.9	9.4	8.0	11.5	10.1	11.8
400	12G	Gnr	Y	670	11.9	3.1	9.3	6.2	8.0	5.0	9.8	6.7	9.9	6.8	11.7
400	12L	Ldr	Y	584	12.1	3.3	8.1	4.8	7.6	4.3	9.2	5.9	8.8	5.5	10.9
400	13C	Cdr	N	766	15.2	2.5	6.1	3.6	9.4	6.9	11.9	9.4	13.4	10.9	13.7
400	13L	Ldr	N	513	15.2	1.9	9.5	7.6	6.7	4.9	8.4	6.6	9.6	7.7	10.3

COHbTA = Predicted final % COHb using WE = 4 and initial COHb = 1
POSTCb = Measured % COHb level by blood method
DCOHb4 = Predicted rise in % COHb using WE = 4 and measured initial % COHb
DCOHb = Measured change in % COHb level
COHbI3 = Predicted % COHb level using WE = 3 and measured initial % COHb
COHbI4 = Predicted % COHb level using WE = 4 and measured initial % COHb
DCOHb3 = Predicted rise in % COHb using WE = 3 and measured initial % COHb
COHbT2 = Predicted final % COHb using WE = 2 and initial COHb =
COHbI2 = Predicted % COHb level using WE = 2 and measured initial % COHb
DCOHb2 = Predicted rise in % COHb using WE = 2 and measured initial % of COHb

DCOHb = Rise in % COHb level
COHb2, 3, 4 = Absolute % COHb using WE = 2, 3, 4
COHbo = Initial % COHb level
Exp = Exposure.
Pos = Position.
Cdr = Commander.
Ldr = Loader.
Gnr = Gunner.

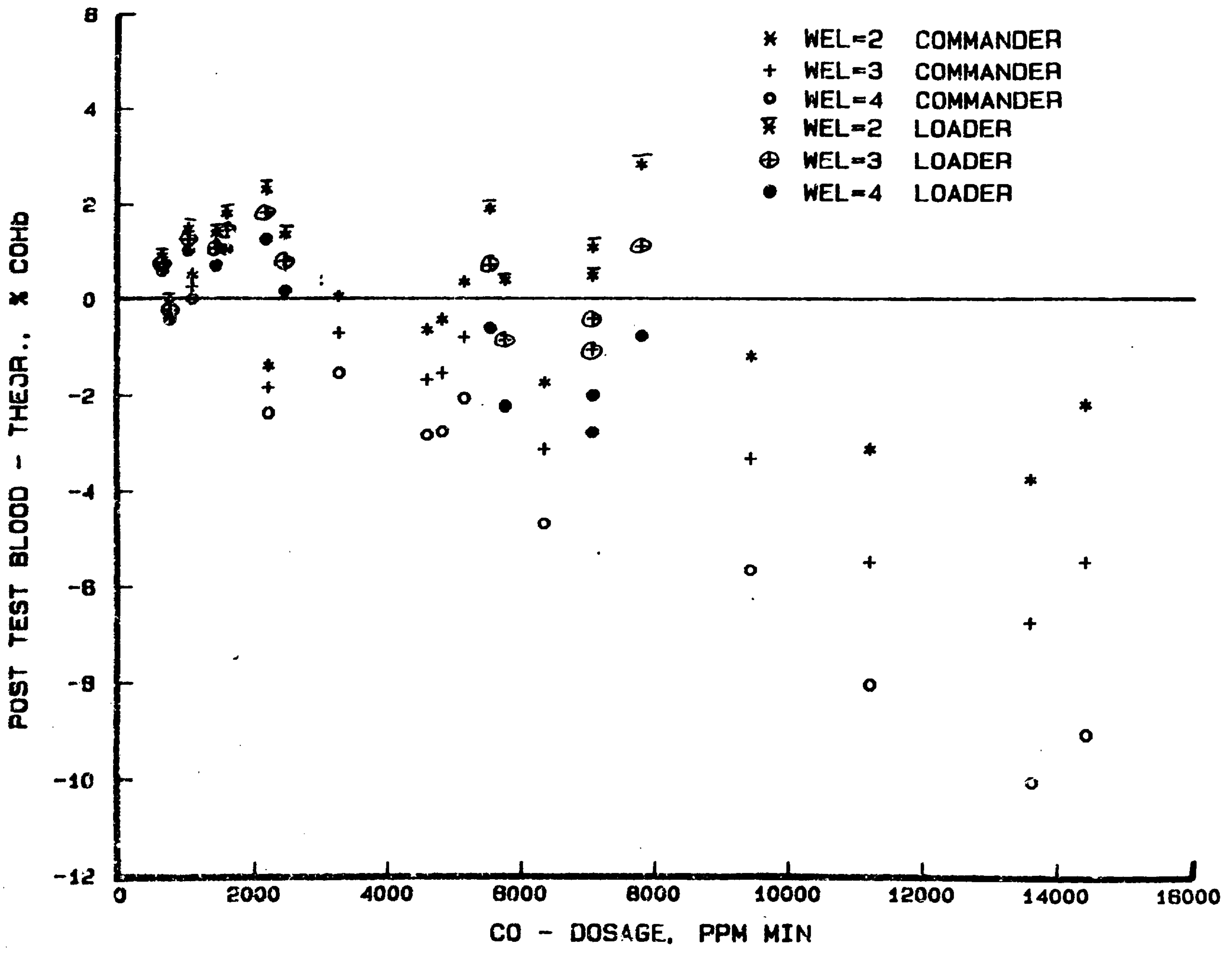


Figure 1.5-1. Post-test blood - theoretical (modified equation) versus CO dosage.

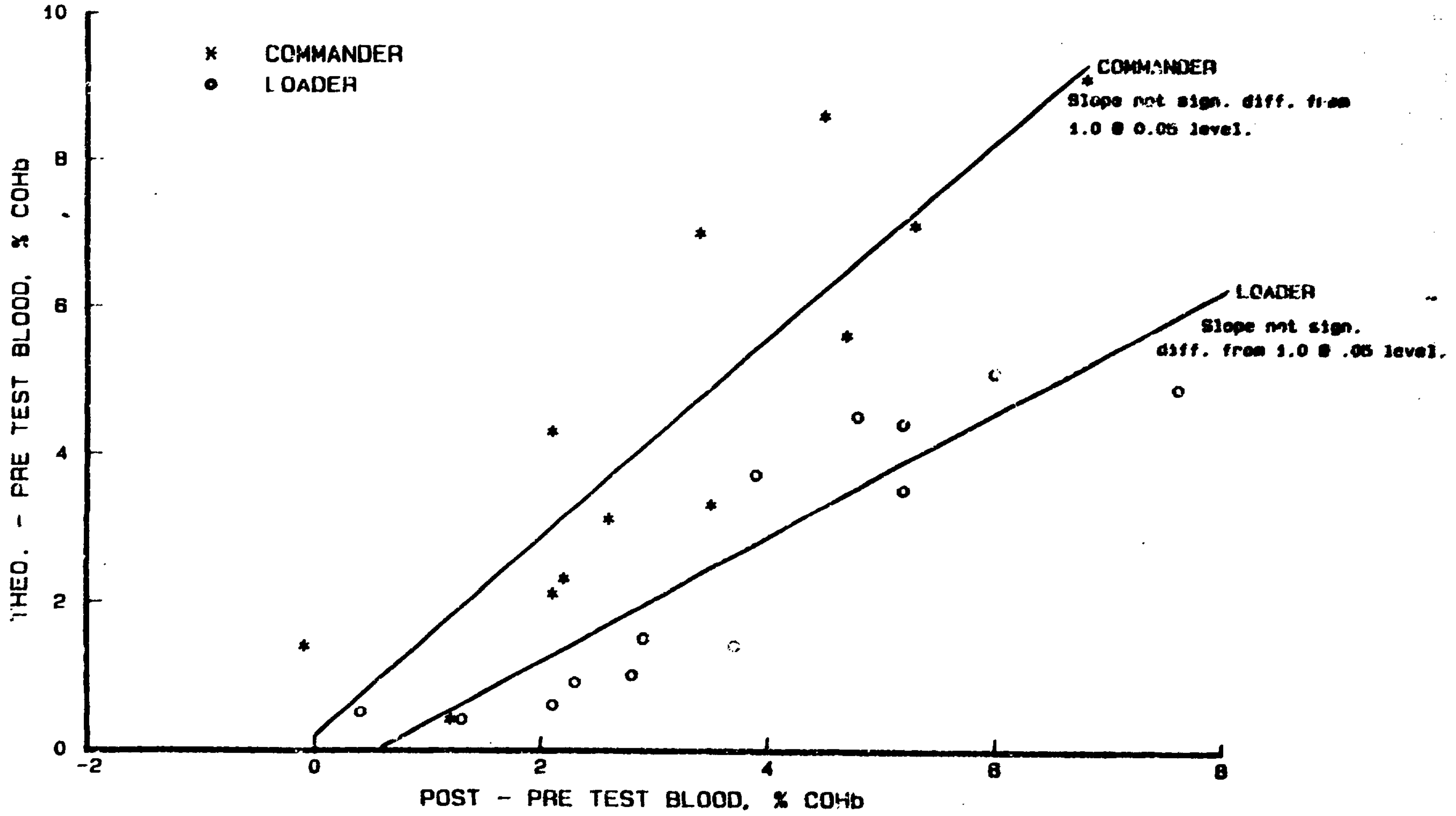


Figure 1.5-2. Post- and pre-test blood versus theoretical pre-test blood (modified equation: WEL = 2).

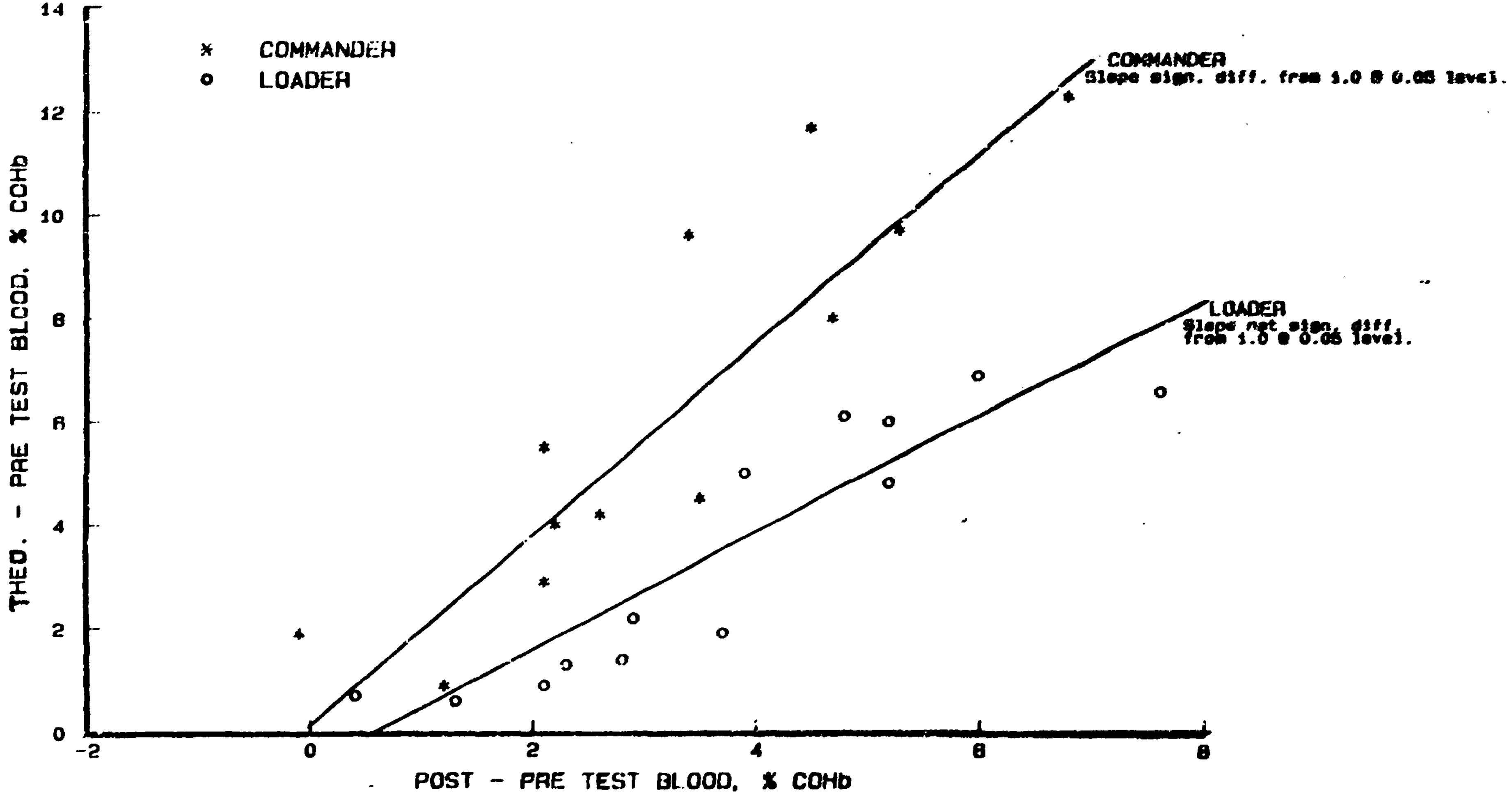


Figure 1.5-3. Post and pre-test blood versus theoretical; pre-test blood (modified equation: WEL - 3).

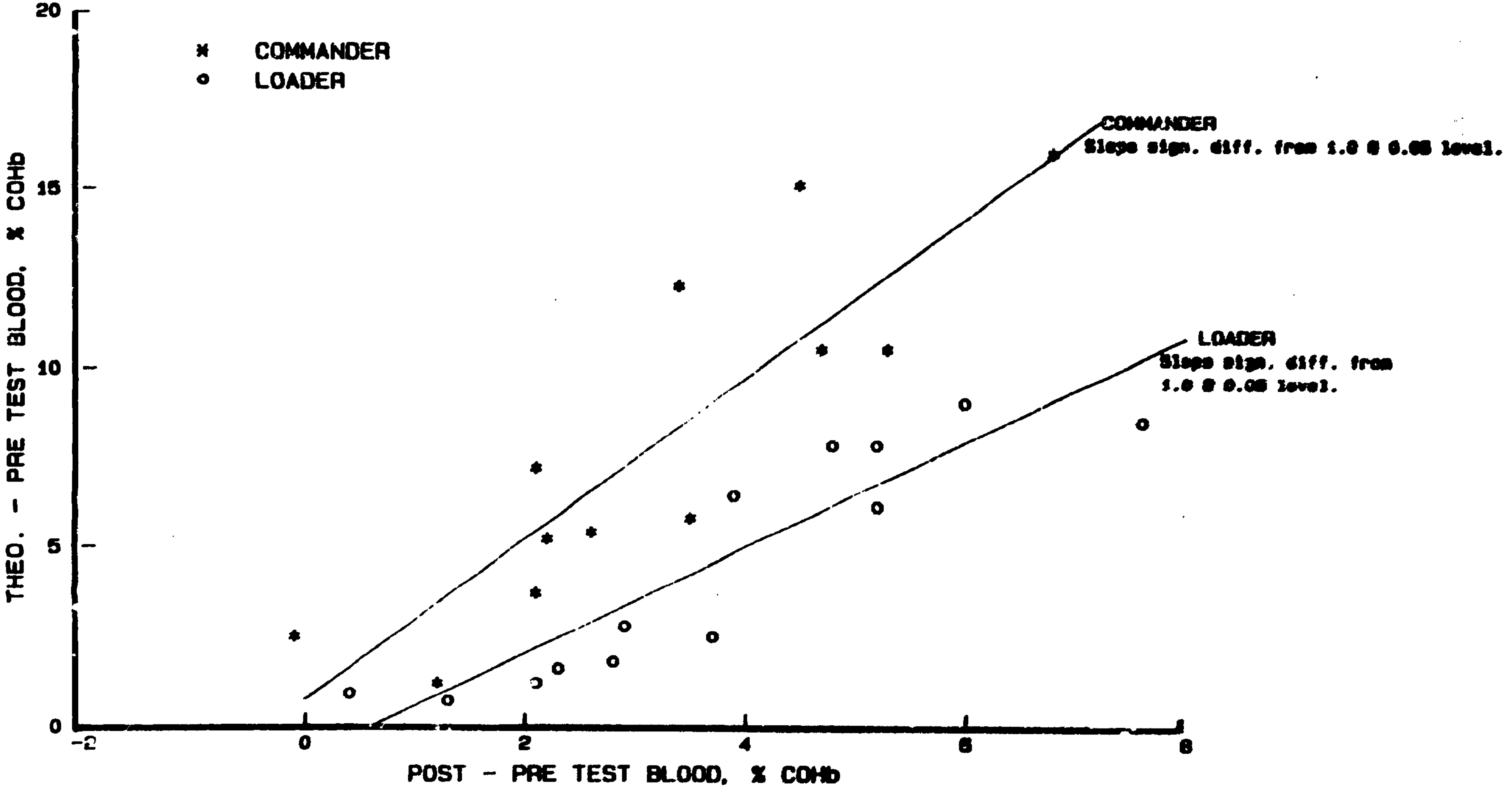


Figure 1.5-4. Post and pre-test blood versus theoretical; pre-test blood (modified equation: WEL - 4).

TABLE 1.5-2. RISE IN % COHb (THEORETICAL VERSUS MEASURED)

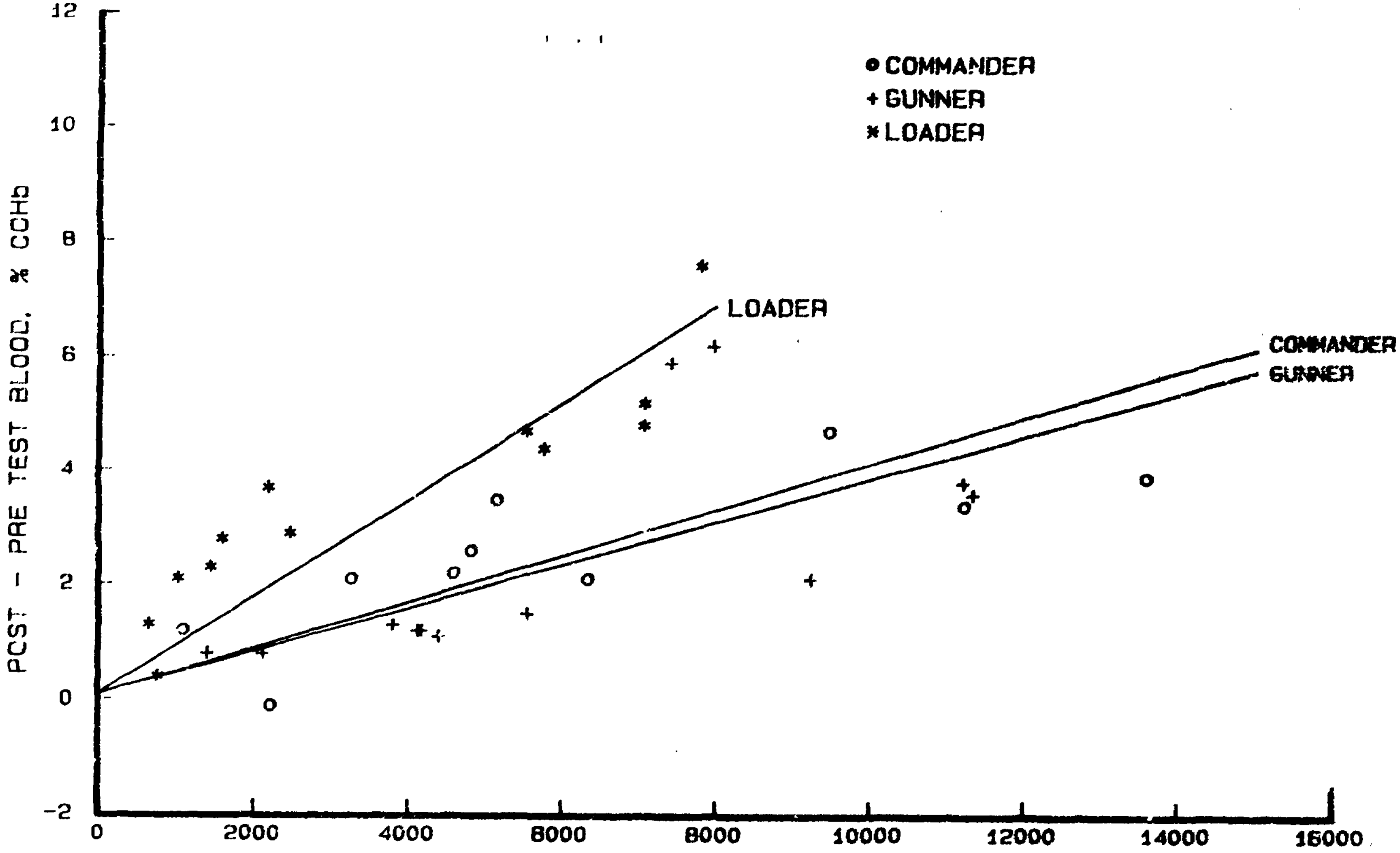
Position	Work Effort Level	Slope	SD % COHb
Commander	2	[a]1.33	1.46
	3	[b]1.79	1.98
	4	[b]2.22	2.51
Loader	2	[a]0.84	0.79
	3	[a]1.13	1.06
	4	[b]1.46	1.36

[a] Slope not significantly different from 1.0 at the 0.05 level.
[b] Slope significantly different from 1.0 at 0.05 level.

Based on these data it seems that work effort level 2 best approximates the actual % COHb in the blood of sedentary personnel for this population. At work effort level 2, the slope does differ from 1.0 but is not significant. Because the slope is greater than 1.0, the equation tends to overpredict the % COHb for sedentary personnel. A slope of less than 1.0 would indicate an under prediction with no margin for error. Consequently work effort levels 3 and 4 tend to significantly overpredict for sedentary personnel so that neither value is considered a reasonable approximation.

The work effort demonstrated by the loader tends to produce a higher rate in the rise of % COHb than the other two positions. This is clearly indicated in the plots of Figures 1.5-2, -3, and 4. At work effort level 2, the slope (0.84) is less than 1.0. While this is not significantly different, it indicates that no margin for error would be involved for the loader. At work effort level 3, the slope (1.13) is greater than 1.0 (though not significantly) indicating that some error margin is involved. Consequently it would seem that the revised equation at work effort level 3 is the preferred value of physical stress for the loader. However, it should be pointed out that the loader was not exposed to CO dosages greater than 8000 ppm-min. It is not known therefore that the predictive values above the 8000 ppm-min dosage would continue to be the best approximations. Only further testing above those levels would resolve which work effort level should be used. The slope at work effort level 4 was significantly different from 1.0 at 0.05 level. The equation significantly over predicts at this level.

(5) Procedures (instruments for measuring % COHb levels). The COHb measurements were performed on site before and after each firing episode. The blood samples were run in duplicate on an Instrumentation Laboratories CO-oximeter, Model 282 and the alveolar air samples were measured on a Mini CO Brand portable CO analyzer which was calibrated against NBS gases before and after each test trial.



POST – PRE TEST BLOOD, % COHb
vs. CO DOSAGE (PPM MIN)

(6) Alveolar % COHb versus blood % COHb. Figure 1.5-5 is a graphical representation of alveolar versus COHb blood levels for the combined pre- and post-test data. The figure includes the regression equation for the data as well as the regression standard deviation and correlation coefficient. Figure 1.5-6 is a similar graphical representation as the previous figure but excludes one outlier data point. Both regression lines indicate that the two methods (alveolar versus blood), for measuring % COHb blood levels, differ significantly.

Figure 1.5-7 presents a graph of the incremental increase in blood COHb levels comparing pre- and post-test measurements for both alveolar and blood methods of measurement. A significance test on the slopes indicate that they are not significantly different from 1.0 at the 0.05 level. While the two methods differ with respect to determining absolute COHb blood levels, they do not differ with respect to determining incremental increases in % COHb levels.

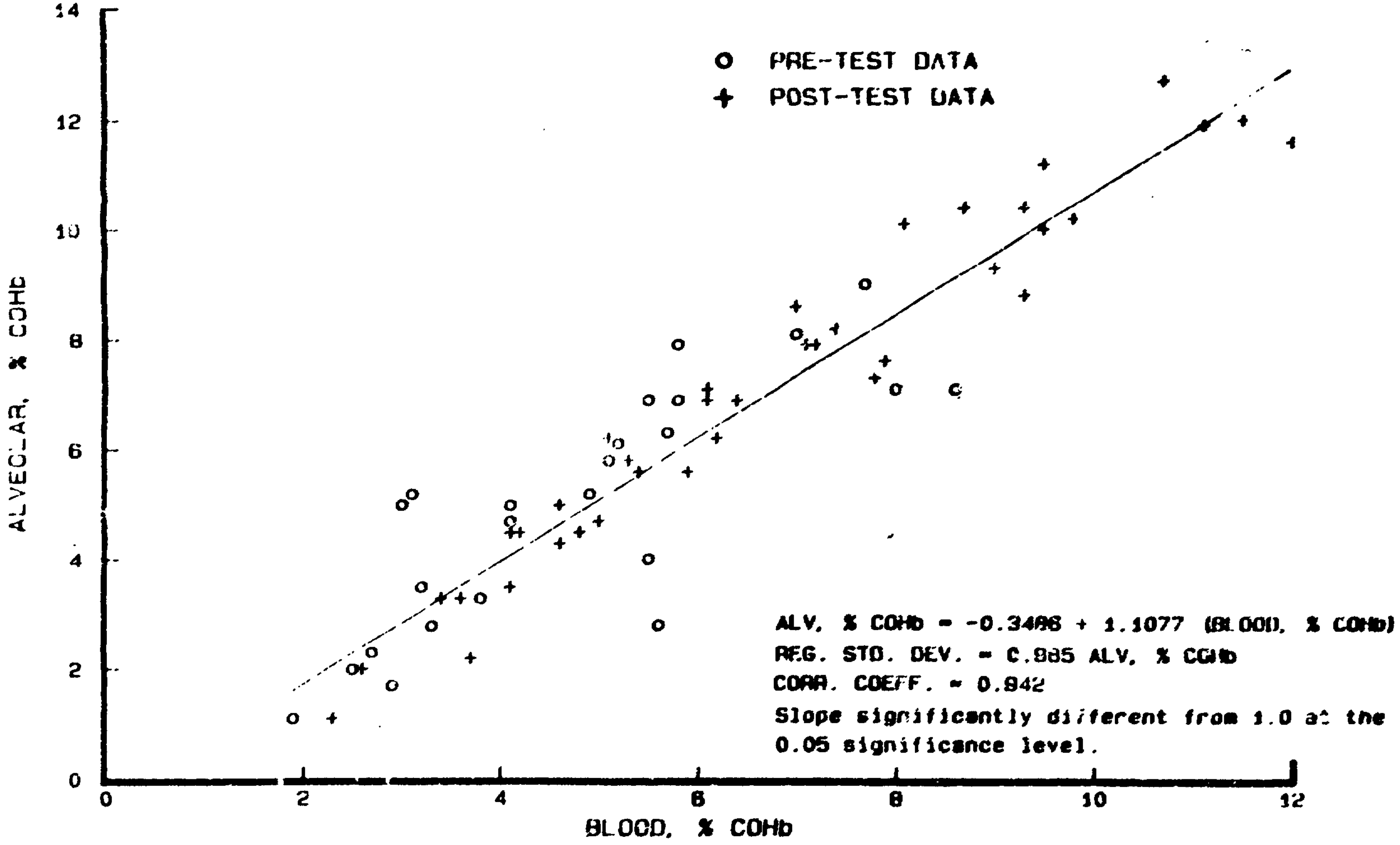
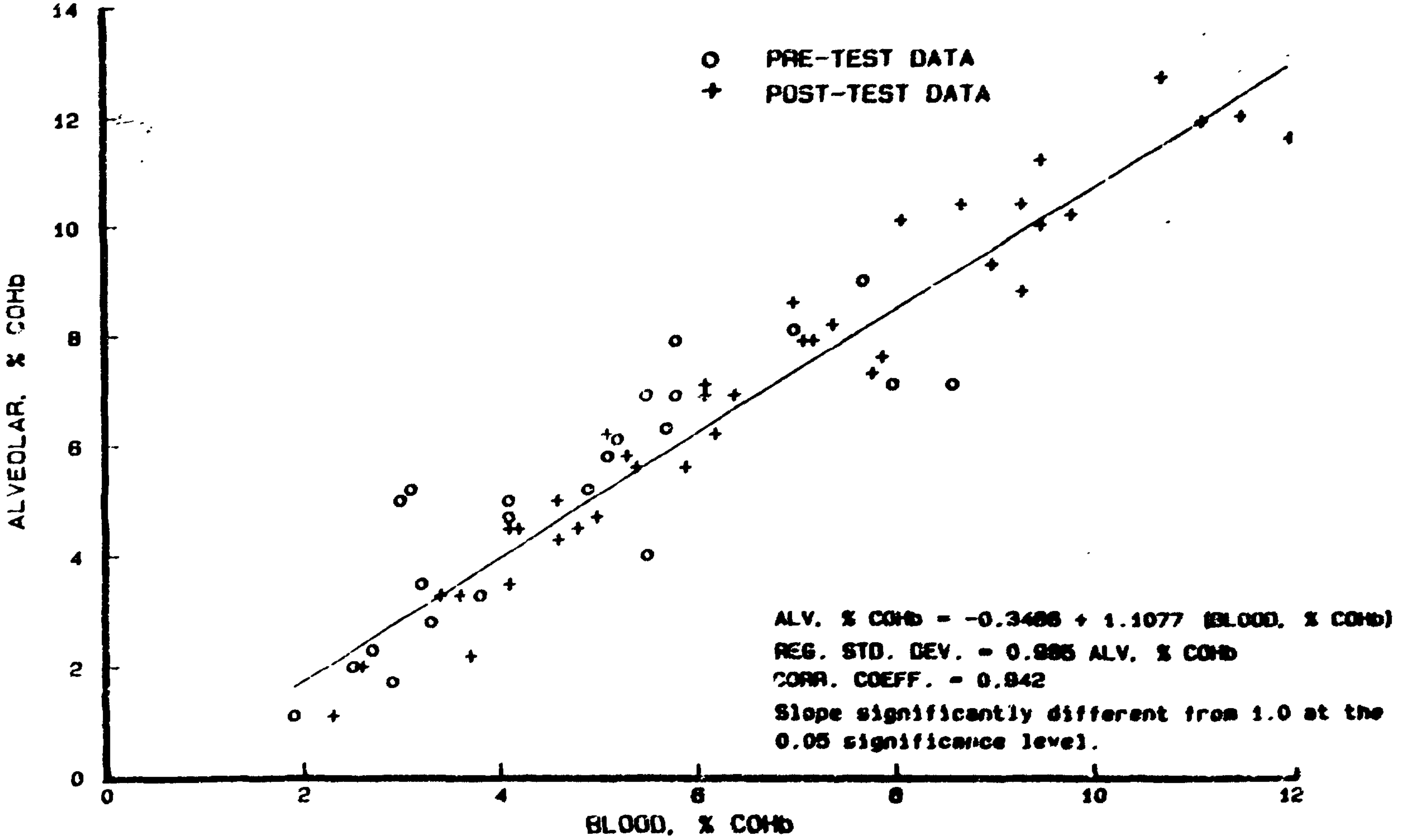


Figure 1.5-5. Alveolar, % COHb versus blood, % COHb (includes one outlier at X=5.6, Y=2.8).



ALV. % COHb = -0.3486 + 1.1077 (BLOOD, % COHb)
REG. STD. DEV. = 0.886 ALV. % COHb
CORR. COEFF. = 0.942
Slope significantly different from 1.0 at the
0.05 significance level.

Figure 1.5-6. Alveolar, % COHb versus blood, % COHb (excludes one outlier at X=5.6, Y=2.8).

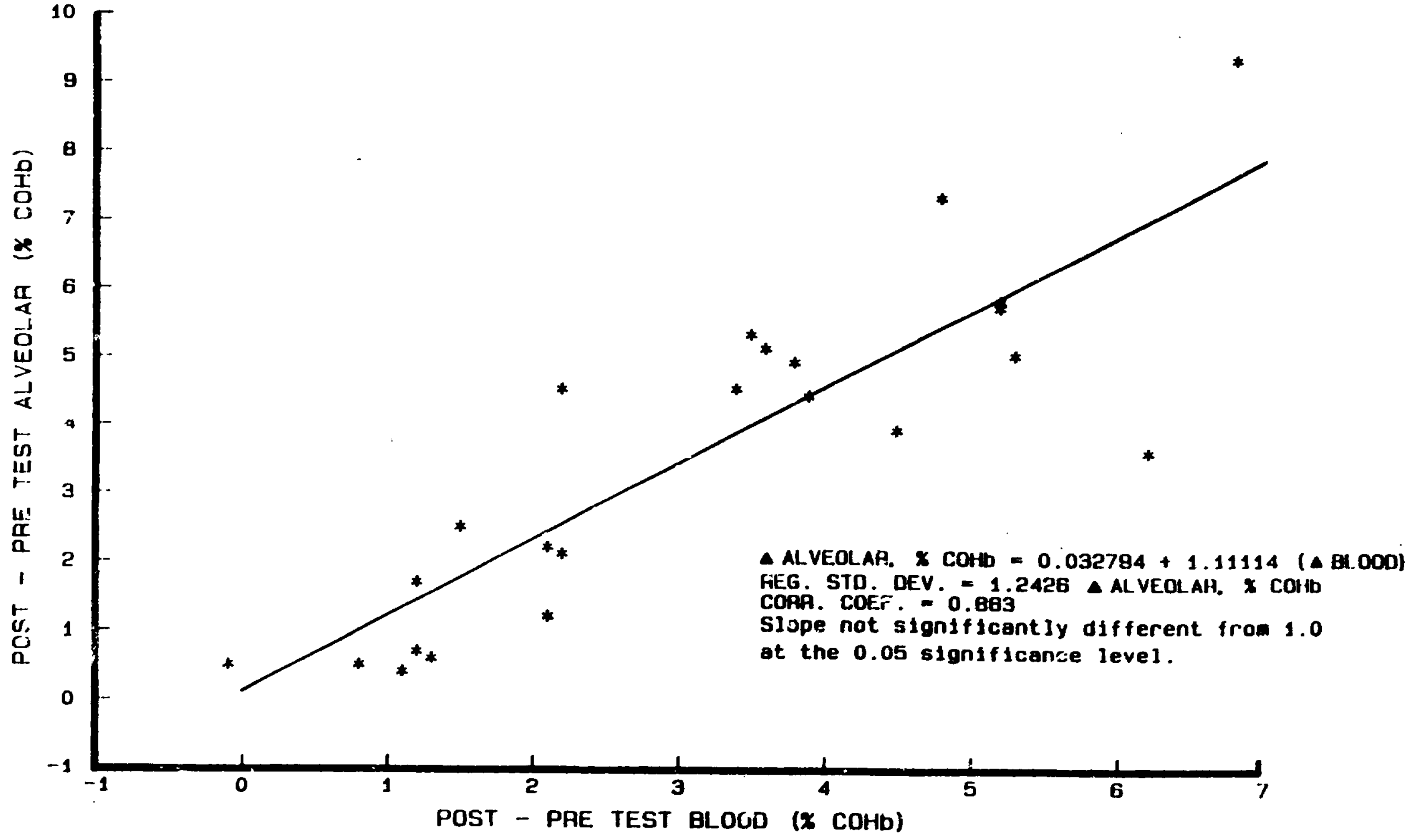


Figure 1.5-7. Post- and pre-test blood (% COHb) versus post- and pre-test alveolar (% COHb).

6. CONCLUSIONS

a. This study was implemented to answer the question: Is the C-F-K equation as currently used by the U.S. Army overpredicting increases in COHb blood levels for combat crew members exposed to weapon fire in enclosed ground combat vehicle? The results of this study support the hypothesis that overprediction is occurring.

b. A comparison of the predicted change in % COHb versus the actual measured change in % COHb indicates that the predicted increases are significantly higher at work effort levels 3, 4, and 5.

c. The mean initial % COHb level for all participants was 3.6% with a standard deviation of 2.2 and a range of 1.2 to 8.6. The use of 1% as the initial COHb level for calculating absolute % COHb is questionable.

d. The revised modified C-F-K equation indicates that WEL 3 best approximates the actual % COHb change for the loader's position and WEL 2 best approximates the actual % COHb change for the remaining two positions rather than WEL 4.

e. It is suspected that the incremental increases in % COHb are greater for nonsmokers than for smokers.

f. The alveolar % COHb measurements are slightly higher than blood measurements.

g. The increment of % COHb levels as measured by the alveolar method are not significantly different than the blood measurements.

USACSTA FIELD TEST PROTOCOL

A. DESCRIPTIVE INFORMATION:

1. Project Title. Field Experiment in Support of Verifying the Predictive Quality of the Coburn-Forster-Kane (CFK) Equation.

2. Principal Investigator(s): Martin Mossa (STECS-SO-S) (X34756)
Thomas Lucas (STECS-DA-M) (X33133)

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3. Study Start Date: Following protocol approval and to be submitted for renewal bi-annually.

B. BACKGROUND:

1. During CY 1976, HEL undertook a critical examination of both the standards applied and methods used by the Army in evaluating human exposure to gaseous carbon monoxide (CO) for transient and steady state type exposures. Of particular concern was the brief high-level transient exposure typical of firing weapons from enclosed ground combat vehicles. As a direct result of that study) and subsequent coordination with various activities of the Army Surgeon General, the Development Community, TRADOC and TECOM, the exposure standards of MIL-STD-1472C and evaluative procedures of MIL-HDBK-759A (ref 3) were revised to reflect a more realistic approach to the problem. The new approach involved predicting percent carboxyhemoglobin (COHb) in the exposed persons blood by using an empirical equation developed by researchers several years earlier. The predictive technique used by the Army is described in detail in reference 3; following the prediction of COHb blood level, the values are then compared with the standards specified in MIL-STD-1472C to determine whether any hazard exists and the extent of the hazard, if applicable.

2. The researchers (Coburn, Forster, Kane) (CFK) relied exclusively upon laboratory results. Although the empirical equation which the researchers developed was based exclusively upon measurements of the exposed subjects' COHb blood levels by both alveolar air and blood-sampling analyses, and although only individual episodic exposures were involved in the experiments, the equation was accepted by the Army medical community as applicable for use with multiple exposures typical of the exposure scenario in live-fire training or in actual combat.

3. The CFK equation has not been verified by data obtained from actual field tests and although the modified CFK equation of MIL-HDBK-759A that the Army now uses is applied conservatively (i. e., ventilation rate of exposed persons is intentionally assumed to be high), there is a pressing need to quantify the predictive quality of the CFK equation since we are using it to assure an appropriate evaluation of the toxic hazard for each system. A positive means of doing that is to collect actual CO exposure data in a field setting and compare these data to modified CFK equation predictions.

4. Recently, an occupational medicine residency project was completed (ref 5) which suggested, in part, that the modified CFK equation may be significantly overpredicting the COHb blood levels of exposed occupants of ground combat vehicles (prototype LAV, M60A3, M109). In addition, unpublished data (ref 6) obtained by the Defence and Civil Institute of Environmental Medicine (DCIEM-Canada) lends credence to the belief that these overpredictions may be as much as 40 to 50 percent. Finally, researchers at the Health Effects Research Laboratory (EPA) at Chapel Hill, NC, also support the thesis of CFK equation overprediction based upon their recent findings in conducting a research program which they and the Army Medical Bioengineering Research and Development Laboratory (Ft Detrick) jointly sponsor.

5. Based on the above, it would be advantageous to obtain sufficient data to verify statistically the degree to which overpredictions are now being made in evaluating CO exposure and to adjust, as required, the modified CFK equation empirical constants to increase the potential of predicting COHb blood levels realistically. Not to obtain such data risks the potential of obtaining results of toxic fumes tests; this could result in erroneous rejection of valid hypotheses made before testing (i.e., rejection of a system as unsafe which is, in fact, safe).

6. The data obtained would be used to revise, as required, the modified CFK equation given in Reference 3 (MIL-HDBK 759A). Any necessary revision of the equation would be acted upon by HEL and coordinated with responsible activities of the Army Surgeon General and TECOM, pursuant to soliciting the necessary approval for revising MIL-HDBK 759A.

C. OBJECTIVE:

1. The proposed research is categorized as a group of field experiments which use ground combat vehicles already safety-certified. As indicated previously, the research is intended to provide sufficient data to:

a. verify that the modified CFK equation as now being used is overpredicting the percent COHb blood levels measured in subjects exposed to CO emissions resulting from ground combat vehicle operations including weapons fire, and

b. adjust the CFK equation given in MIL-HDBK-759A to predict reliably, accurately, consistently, and with realistic conservatism, the COHb blood levels of exposed soldiers, assuming that the hypothesis of a. above is confirmed.

D. METHODOLOGY:

1. Participants: The participants will consist of military/civilian test personnel, organizationally tied to the US Army Combat Systems Test Activity at Aberdeen Proving Ground, whose job function is to act as crew members during development or special testing of combat vehicle systems already safety-certified and specifically during weapon-firing episodes. It is not necessary that they be experienced other than to perform the tasks for the specific test being conducted, and that they be willing to both act as supporting subjects/participants in pursuit of the test objectives noted above. They must also be willing to be subjected to biological monitoring which, in part, will include periodic drawing of blood samples from their arms and breathing into and air bag.

2. Test Apparatus:

a. Due to the limited financial resources available for these proposed series of field tests, the plan is to implement this program by obtaining the needed data during tests of major combat vehicles (e.g., M1, BFV, LAV, M109, M1E1, M60 Series) when each is scheduled specifically for live firing tests that provide safe, high-level transient exposure to gaseous carbon monoxide (CO) to on-board crew members. Firing of the main/auxiliary weapons under a variety of test conditions (hatches open and closed, engine on and off, vehicle stationary and moving, varying rate of fire) will provide the needed variation of CO exposures. Essentially, these tests are "piggyback" variety.

b. The major instrumentation to be used consists of the following:

(1) Ambient crew space and alveolar CO concentrations will be obtained as follows:

(a) Ambient Crew Space CO Concentration: During mobile tests, a Leybold-Heraeus Binos dual channel nondispersive infrared carbon monoxide analyzer (full scale range is 2500 ppm CO) will be mounted in the crew compartment to monitor CO concentrations at two positions within the test vehicle. During stationary tests, Leybold-Heraeus single channel, dual range (full scale ranges 1,000 and 10,000 ppm), nondispersive infrared analyzers mounted in a mobile toxic laboratory and connected to the test vehicle by Teflon tubing will be used to monitor CO concentrations at four positions within the test vehicle. Test data will be recorded on either Metrosonics dl-331 digital data loggers (mobile) of Nicolet 4094 oscilloscopes (stationary).

(b) Alveolar CO Concentrations: For all tests, a Bechman Model 865 triple range nondispersive infrared analyzer will be used to analyze the samples collected in evacuated polyethylene bags. Test data will be recorded on Nicolet 4094 oscilloscopes.

(c) All analyzers will be calibrated with zero air and appropriate range span gases. Analyzers used for crew space monitoring will be calibrated at 0, 500, 1,000, and 2,500 ppm (nominal). Analyzers used for alveolar air monitoring will be calibrated at 0, 25, and 50 ppm (nominal). All calibration gases will be analyzed and certified by the supplier and will be checked against NBS Standard Reference Materials by gas chromatography. These devices/recorders/supporting items will either be installed in the vehicle or in an accompanying instrumentation van, as appropriate.

(2) Alveolar CO specimens will be collected in evacuated polyethylene bags, each equipped with a three-way valve and disposable mouthpiece. The collection technique (Stewart et al (ref 7)) will be followed and alveolar CO concentrations determined immediately afterward with the instrumentation specified in the preceding paragraph.

(3) Blood samples, for determining the percentage COHb, will be obtained before and after completion of each monitoring scenario. The blood will be drawn into evacuated tubes containing ethylene-diamine-tetraacetic acid (EDTA). According to Collison et al (ref 8), these blood samples may be shipped or stored in stoppered test tubes at refrigerator temperatures for at least 10 days without significant loss of COHb concentration. Blood COHb concentrations will be determined by spectophotometeric methods on a CO-Oximeter following the procedure developed and standardized by the Armed Forces Institute of Pathology (unpublished). Even though the precision of CO-Oximeter results is reduced (+/- 0.2%) from that obtained by the gas chromatograph, the precision is adequate for biologic monitoring applications. It is expected that the blood specimens will be analyzed for COHb content by the laboratory at Johns Hopkins Hospital supervised by Dr. Richard Traystman.

(4) Blood for hemoglobin electrophoresis and complete blood count will be drawn before CO exposure and submitted to the Kirk Medical Department Activity at APG for analysis. The submission of the specimens will be in accordance with the SOP at the clinic.

c. Procedures:

(1) The experimental scenario will be a function of the type of firing test scheduled by USACSTA as indicated above in subparagraph 2a.

(2) The test crew for each field test will be briefed as to the test purpose/objectives/procedures.

(3) Other than a practice session during which the crew will be taught how to breath into the polyethylene bag for collecting the alveolar CO specimens, no training of personnel will be necessary.

(4) Data-collection procedures are summarized as follows:

(a) Following an explanation of the purposes/objectives of the test program, each participant will be asked to complete/sign the "Consent Explanation Sheet and Volunteer Agreement" form

(b) A demographic questionnaire (Appendix B) will be administered to all test participants before testing by a test team member who will instruct the subjects in the proper technique of providing valid alveolar CO specimens. Appendix C provides the detailed procedure to determine the COHb level from the alveolar specimen;

(c) For each crew member, an alveolar CO specimen and blood sample will be obtained before a firing sequence or anticipated episodic exposure. Both alveolar CO and blood specimens will be collected outside the test vehicle;

(d) In addition to COHb determinations, blood specimens will be obtained for hemoglobin electrophoresis and a complete blood count (total hemoglobin, red cell indicies, and white cell count with differential);

(e) CO levels will be monitored and recorded continuously during the scenario. Air samplings will be obtained from the breathing zones of all crew members. Wherever practical, analyses and recording equipment will be located in the crew compartment; remote monitoring/recording will be employed when either the scenario or space prevents the equipment from being placed in the vehicle; and,

(f) additional data to be obtained include test conditions, configuration, meteorological conditions, personnel participating, test conductor, ect.

E. EXPERIMENTAL DESIGN:

1. On the basis of the details presented in the preceding paragraphs, no experimental design is unique to these series of proposed field tests. As stated in paragraph D2a above, the specific vehicle tests to be selected will involve major vehicle systems, already safety-certified, which are scheduled for live firing tests where the exposures to CO emissions are expected to be both of the transient type and of fairly high level, typical of firings with the main or auxiliary weapons. Accordingly, the scenarios for each test may vary significantly, but the commonality that exists will be evident in that vehicle crews will have been exposed to various levels of CO, and that these personnel will be biologically monitored to determine, by two independent means (alveolar CO and blood specimens), the percentage of COHb in their blood.

F. DATA ANALYSIS

1. Description:

a. In accordance with statements made in the BACKGROUND Section (Paragraph B) of this protocol, it is suspected that the CFK equation (ref 3), as the Army is now using to evaluate the criticality of human exposure to CO, is overpredicting significantly (to 50 percent) the percentage COHb in the exposed person's blood. This belief results from several sources of information including the data presented in Figure 1 the results presented in Reference 5, and in personal discussions with the author, and preliminary results of the multi-year research program sponsored jointly by the AMBRDL (Ft Detrick) and the HERL (ERA at Chapel Hill, NC). Also, the required ventilation values for crew members, now used in the modified CFK equation (24 and 18 liters for firing and nonfiring episodes, respectively) may be overly conservative and contribute significantly to overpredicting percent COHb blood levels.

b. It is intended to develop plots of Alveolar CO (ALCO) versus percent COHb (from blood specimens) versus CFK equation predicted percent COHb level for each vehicle tested. Linear regression techniques will be employed, including the calculation of 95 percent confidence bands, correlation coefficient, and regression standard deviation. Composite plots composed of test data obtained from all vehicles will be similarly treated and compared to the individual plots. The results of this type analysis should be a recommendation whether a revision to the modified CFK equation is necessary. Any recommendation for revision that results from these investigations will be coordinated with the appropriate activity(s) of the Army Surgeon General.

G. HUMAN USE:

1. Risk: The risk for participants is minimal as all vehicles intended for use in the field tests will already have been safety-certified. The risk for participants should be less than ordinary since they will be medically monitored during the tests. This would probably not have been the case if the firing tests had been performed apart from the subject of this protocol. Although the collection of ALCO and blood specimens does pose some element of risk to the participant from a viewpoint of a slight invasion of his physical being, competent medical personnel will be in attendance during the testing, and the individual's participation is completely voluntary.

2. Safety Procedures:

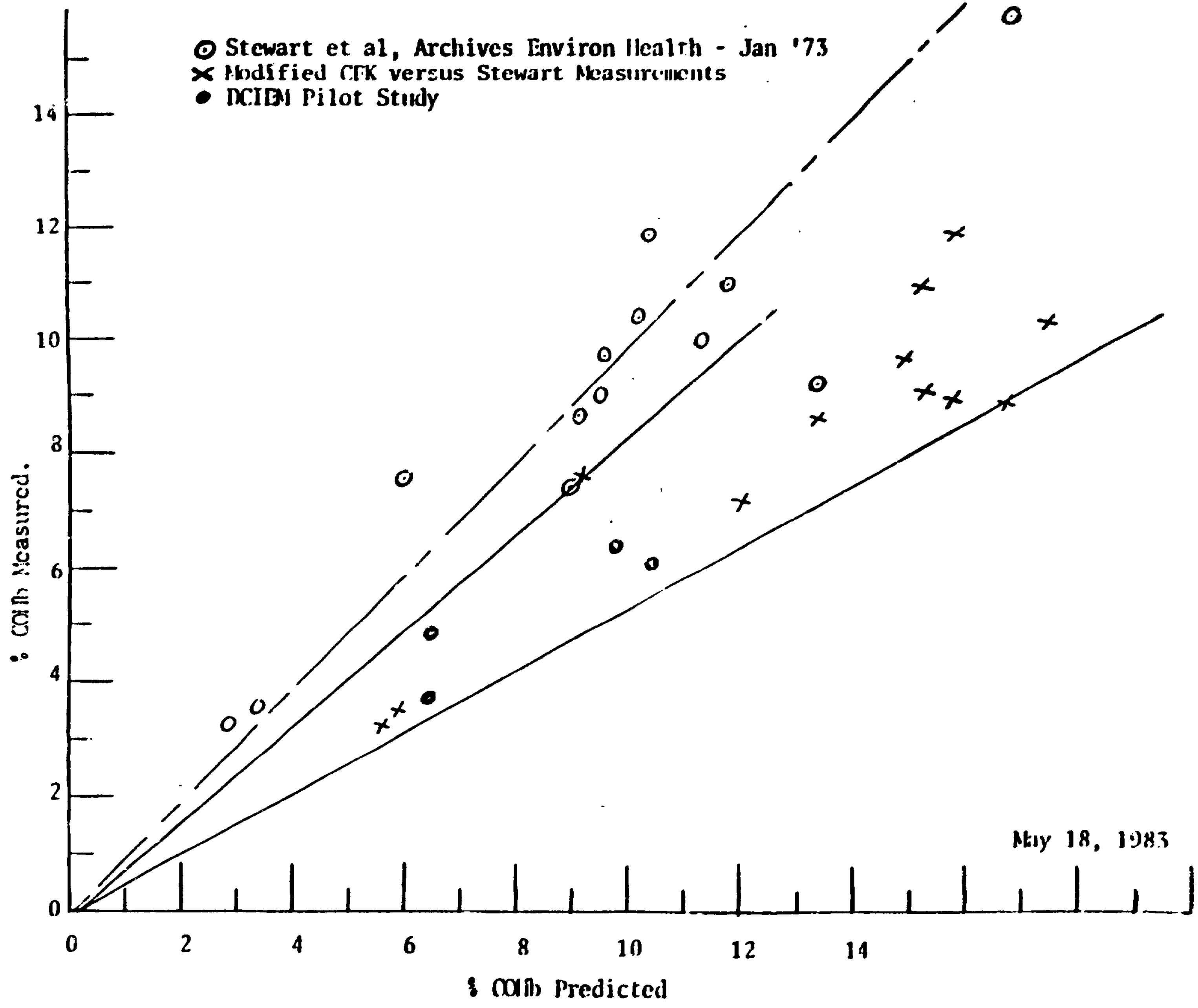
a. SOP 385-67 (ref 10) other pertinent SOP's as well as TOP 2-2-614 will be adhered to during all testing. Furthermore, safety releases issued for specific test items will be strictly observed.

b. The policies and procedures of AR 70-25 governing the use of volunteers as subjects in DA research apply to this protocol only in the sense that the subjects will be biologically monitored/supervised by a medical officer who will also be obtaining blood samples at appropriate intervals during the testing. It is emphasized that although the civilian and military participants will be exposed to toxic gases, the vehicles/equipments used in the tests have already been safety-certified and the participants are not experimental subjects in the context of AR 70-25.

c. While the risks are determined to be minimal, in the event of an emergency, medical personnel will be available on site to administer emergency treatment. Appropriate medical facilities will be available to administer such treatment as 100 percent oxygen. Arrangements will be made in advance to fly potential victims to the Shock Trauma Unit at University Hospital if conditions warrant.

3. Participants will be informed as to the results of monitoring and their significance. Appropriate entries will be made in their health records. The data collected will respect the confidentiality of individuals.

4. Pertinent questions by the research subjects may be submitted to the principle investigator or the medical surveillance officer.



May 18, 1983

Figure 1. % COHb Measured versus Predicted.

CONSENT EXPLANATION AND VOLUNTEER AGREEMENT

DATE————————— TIME—————————

ORGANIZATION: US Army Combat Systems Test Activity, Aberdeen Proving Ground, MD. 21005-5059

PROTOCOL TITLE: Data for Empirical Modification of the Coburn-Forster-Kane Equation

PRINCIPAL INVESTIGATOR(S): Messrs. Martin Messa (STECS-SO-) (X34756) and Thomas Lucas (STECS-DA-M) (X33133)

ASSOCIATE INVESIGATOR(S): Messrs. C. Herud and L. Brown (STECS-EN-PC) (X33165)

CONSULTANT: Mr. S. Steinburg (AMXHE-CC) (X35956)

MEDICAL SURVEILANCE OFFICER(S): Dr. Melvin Tockman and Dr. Richard O. Dockins

PARTICIPATION INFORMATION: We are seeking volunteers to participate in a research study conducted by the US Army Combat Systems Test Activity at Aberdeen Proving Ground in conjunction with the Johns Hopkins Center for Occupational and Environmental Health. It is very important that you understand the following general principles which apply to all participants in the studies we conduct.

a. YOUR PARTCIPATION IS ENTIRELY VOLUNTARY.

b. YOU MAY WITHDRAW FROM PARTICIPATION IN THIS STUDY OR ANY PORTION OF THE STUDY AT ANY TIME.

Furthermore, withdrawal from the test will not prejudice any condition of employment or result in any adverse personnel action. Also, non-participation or withdrawal will not affect your ability to receive care at the Johns Hopkins medical institutions and will in no way affect the quality of care you might receive.

c. AFTER YOU READ THE EXPLANATION, PLEASE ASK ANY QUESTIONS THAT WILL PERMIT YOU TO FURTHER CLARIFY EITHER THE NATURE OF THE STUDY OR SEGMENTS WHICH ARE NOT CLEAR.

Your participation will be limited to one exercise involving approximately one to two hours of your time whereby you will be monitored for carbon monoxide exposure.

NATURE OF THE STUDY: This study is being conducted to monitor the exposure of crewmen to carbon monoxide under a variety of test/operational conditions. If you agree to participate, we will monitor your exposure to carbon monoxide during live fire exercises where the production of carbon monoxide is considered representative of expected operational situations. Your exposure to carbon monoxide will be monitored as follows:

a. Sampling for carbon monoxide in the air you breathe.

b. Measuring carbon monoxide in the air you exhale into a plastic bag.

c. Measuring the level of carboxyhemoglobin in your blood both before and after the test. This will require drawing two samples of blood totaling about 20 milliliters (about 4 teaspoons).

In addition to measuring the levels of carbon monoxide in your blood and breath you will be asked to have a physical examination prior to the test exposure and a lung function test will be done. Also, just prior to the test you will be asked to complete a questionnaire containing questions about smoking, previous lung problems and consumption of alcohol (all of which are thought to affect the levels of carbon monoxide in the blood). Of course, if you feel a question is too personal or sensitive you have the right to refuse to answer. However, all information collected on these questionnaires will be held in strictest confidence.

Also, while you are in the test vehicle you will have a microphone attached to your throat to measure your breathing rate and you will have pads placed on your chest to monitor your heart rate.

BENEFITS: Although there is no direct benefit to you personally, the information obtained from the study will enable the Army to validate the standards now used for exposure to carbon monoxide and may help enhance crew safety.

RISKS, INCONVENIENCES AND DISCOMFORTS: There is a risk involved with exposure to carbon monoxide. However, the risk for participants in this study are minimal because all the vehicles being used have already been safety certified. Some participants will feel discomfort when stuck by a needle to draw blood and may have a small bruise at the puncture site.

NUMBERS OF PARTICIPANTS IN THE STUDY: 39

CONFIDENTIALITY OF RECORDS: Results of this test will be part of published reports. Participants will not be personally identified in these reports. You will be informed of the results of this test and their significance. All personal information collected will be confidential and will respect your privacy.

COMPENSATION AND MEDICAL TREATMENT FOR INJURIES/ILLNESS: In accordance with AR 70-25, you are authorized all medical care for injuries or diseases which are the proximate result of your participation in this study. For information related to the rights of research subjects, contact the Post Judge Advocate General's office.

FOR FURTHER INFORMATION RELATED TO TESTING PROCEDURES: Please contact any of the above listed persons for additional information.

Consent Form

The nature and purpose of the experiment, the risks involved and the possible complications have been explained to me and I agree to participate in this study.

Signed________________________________

Witness________________________________

22nd Department of Defense
Explosives Safety Seminar

Safety and Handling of Hydrazine

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Abstract

Hydrazine products are widely used as chemical building blocks oxygen scavengers, chemical explosive intermediates, monopropellants and bipropellants. Although these forms of hydrazine have had a long history of safe and successful use, hydrazine has recently received much attention due to its toxic properties.

The latest toxicological information on hydrazine and the regulations governing its use are reviewed. Hydrazine's nature, what to do about personnel exposure, how it can be absorbed into the body and what effects exposure may create are all discussed. Discussion will focus on how employee exposure to hydrazine can be minimized by simple and effective engineering controls, supplemented by mandatory use of protective equipment and proper handling procedures. Training of employees to recognize the hazards involved and safe procedures to be used is the most important element in minimizing the hazard potential with any chemical.

Introduction

Hydrazine's original use was as a rocket fuel in the ME-163 German fighter plane during World War II. Today, hydrazine propellants include anhydrous hydrazine (AH), monomethyl hydrazine (MMH) and unsymmetrical dimethyl hydrazine (UDMH) and the 70% aqueous hydrazine (H-70) product. Hydrazine fuels have been historically used as bipropellants with nitrogen tetroxide and as a monopropellant. Hydrazine's use as a monopropellant, is by its decomposition over a suitable catalyst to produce gaseous products to provide attitude and in orbit control for satelites and spacecraft. Hydrazine is also produced and sold as aqueous solutions (64, 54.4 and 35 weight percent solutions) for application as a corrosion inhibitor/oxygen scavenger; and as a chemical building block for agricultural products, chemical foaming agents and explosive intermediates along with many other uses. A number of hydrazine derivatives including the simple perchlorate, nitrate and azide salts are explosives. Hydrazine derived aminoguanidine derivatives, including 5-aminotetrazole, guanylazide, and tetracene are explosives with tetracene used as an ammunition primer component.

Hydrazine is an important industrial chemical whose historical, present and projected uses are based to a large extent upon its high degree of reactivity. This same property, however, has in the past given hydrazine the reputation of being an unstable and hazardous chemical.

Misapprehension concerning the nature of hazards involved in handling hydrazine started before the compound was isolated, and has continued for years. Curtius (1), who first prepared hydrazine in solution, expressed the conjecture that "the free base is so unstable that it can not exist in the free state." The prediction of Curtius was later proved erroneous by Labry de Bruyn (2), who isolated the anhydrous free base, and reported that "it is a very stable compound, and in contrast to hydrogen peroxide, not explosive. It can be heated above 300°C without being decomposed." Despite this observation, and in spite of other experimental evidence to the contrary, the idea of inherent instability has continued to persist. Although hydrazine products have a long history of safe and successful use, hydrazine has received much attention recently due to its toxic properties. The American Conference of Governmental Industrial Hygienists (ACGIH) and the International Agency for Research on Cancer have listed hydrazine as a suspect carcinogen. Hydrazine products are indeed hazardous commodities, but so are a great many of the chemicals , industry routinely handles. If people are aware of the properties of hydrazine so they can separate facts from misunderstandings and become knowledgeable in the best way to handle hydrazine, then it's safe use can be assured.

Hydrazine Properties

An attempt is made here to summarize some of the available information pertinent to hydrazine safe handling. For this purpose information dealing with anhydrous hydrazine and the aqueous solution products will only be covered. More detailed information is covered in a number of excellent references (3-7).

Physical. Anhydrous hydrazine (N_2H_4) is a highly polar, hygroscopic liquid that will absorb CO_2 or oxygen from the atmosphere. It melts at 2.0°C and boils at 113.5°C (760 mm Hg). Since its density as a solid (1.146/-5°c) is higher than as a liquid (1.024/2°C), there is no danger of rupturing containers under freezing conditions.

Vapor pressures for anhydrous hydrazine are represented by the following empirical equation:

$$\log_{10}P(\text{mm Hg}) = 7.80687 - 1680.745/(t + 227.74)$$

Above the atmospheric boiling point, data is less reliable due to thermal decomposition. Hydrazine and water form an azeotropic mixture which boils at 120.3°C (760 mm Hg) containing 58.5 mole % N_2H_4. Freezing point (Table I) data on the $N_2H_4.H_2O$ system show the compound $N_2H_4.H_2O$ to be a stable solid phase melting at -51.7°C. Eutectics exist at 29.5 mole % (-88°C m.p.) and at 56 mole % (-53.5°C m.p.).

Chemical. From a strictly chemical standpoint, hydrazine is classified as a very strong reducing agent, and a mildly alkaline base. It reacts readily and exothermically with most oxidizing agents, and mineral acids with the speed of reaction depending upon concentration, temperature, and catalytic conditions.

Examples of oxidizing agents include not only the electronegative elements and highly oxidized compounds, but also lower oxides of some metals and even certain metal ions. Hydrazine may be liquid or vapor, concentrated or dilute, free or in combined from. Principal products are usually N_2 and H_2O, but in some cases substantial amounts of NH_3 are produced. Typical reactions include reduction of salts of oxides of copper, iron, silver, mercury and many other similar metals. Reaction MoO_3, Fe_2O_3, MnO_2, HgO, CuO, PbO_2, CrO_3, $AgNO_3$ and Cu $(NO_3)_2$ may be particularly violent with anhydrous hydrazine, although less so with the aqueous hydrazine solutions (ie) 35% hydrazine.

As with many chemicals certain precautions must be observed when handling hydrazine propellants and products. Acids such as hydrochloric, sulfuric, and nitric, and oxidizers like hypochlorites, hydrogen peroxide, permanganates, chromates etc. should be avoided in areas where hydrazine is handled or stored. Again, it is important to recognize that the intensity of the reactions of hydrazine with oxidizers or acids is dependent upon the concentration of the reactants. The lower the hydrazine concentration, the milder the reaction.

Flammability. Liquid anhydrous hydrazine is very stable and non-explosive. In the absence of decomposition catalysts, it has been heated above 500°F with very little decomposition.

Hydrazine vapors, however do present a hazard. Mixtures of hydrazine vapor in air are flammable between the limits of 4.7% and 100% hydrazine by volume. The flammability of hydrazine vapor is decreased by the use of any of several diluents. Nitrogen is generally recommended due to ready availability and cost. The lower explosive limit of a hydrazine-nitrogen-air mixture is a straight line function between 4.7% for air and 38% for nitrogen at 228° to 234°F.

In contrast to most other chemicals, hydrazine has no upper limit to the range of explosive concentrations. Combuction of cold liquid hydrazine is difficult to initiate. Ignition occurs only when the temperature has been raised above roughly 126°F, the fire and flash points for hydrazine. When burning freely in air, hydrazine behaves much like gasoline. However, at elevated temperatures it burns fiercely.

Water solutions of hydrazine at any concentration below 40% cannot be ignited. A 50% solution will burn only near its boiling point, with increasing concentration the burning temperature decreases to about 126°F for the anhydrous product (see Figure 1 and Table I). Water is the best means of combating fires, as it has the combined effect of cooling and diluting the hydrazine below its combustible limit.

Stability. Anhydrous hydrazine and aqueous hydrazine solutions under normal conditions are stable and insensitive to shock and friction. It presents no explosive hazard and storage tests over extended periods have shown negligible decompositions of the products. Decomposition of hydrazine is caused by elevated temperatures and the presence of catalytic surfaces or ion impurities.

At increased temperatures, hydrazine will slowly decompose to yield nitrogen and ammonia. Studies at temperatures up to 500°F have shown that most of the decomposition takes place in the vapor phase, and that the rate of decomposition is a direct function of temperature. No rapid decomposition has been observed, even at 500°F, in the absence of catalytic agents.

Certain metallic ions and metallic oxide surfaces exhibit a marked catalytic effect upon the decomposition of hydrazine. Laboratory studies have shown that chromic, ferric and cupric ions catalyze decomposition of hydrazine at reflux conditions under a nitrogen blanket. At ambient conditions there is no noticeable effect from dissolved ions. A surface area catalytic effect occurs when molybdenum, iron, Raney nickel, rust, copper oxide or cobalt in finely divided form come into contact with hydrazine. A film of hydrazine on iron rust will burst into flames if ventilation is inadequate to keep it cool.

Ignition has also been observed with asbestos, expanded vermiculite, sawdust, rags, paper and some metal powders when moistened with hydrazine and exposed to the atmosphere at room temperature. The phenomenon is similar to the spontaneous ignition of drying oils, starting with slow oxidation under conditions that prevent the dissipation of the heat as fast as it is liberated, and preceding faster as the temperature rises until the ignition temperature is reached. The effect of the porous solid may be either catalytic or simply that of a barrier to dissipation of heat.

Health Hazards

Although anhydrous hydrazine and aqueous hydrazine solutions have a long history of safe and successful use, hydrazine received much attention recently due to its toxic properties. The American Conference of Governmental Industrial Hygienists (ACGIH) and the International Agency for Research on Cancer have listed hydrazine as a suspect carcinogen. Hydrazine solutions are indeed hazardous commodities, but so are a great many of the chemicals industry routinely handles.

Questions of occupational safety and health are never solely a matter of the toxicity of a chemical. They should be a matter of selecting and adopting the proper handling methods. Use of mandatory protective equipment is prudent and appropriate in view of the toxic and physical/chemical properties of the chemical. No chemical is completely safe unless it is properly handled and, it is well known that comparatively hazardous chemicals can be handled safely. Training of employees about the hazards involved and safe procedures to be used is the most important element in minimizing the hazard potential.

Hazardous exposure of personnel to hydrazine should only occur through accidents, since the precautions established for proper handling and storage would protect workers under normal non-accidental conditions. The two types of exposure are: 1) acute, short-term, high-dosage exposure resulting from a massive spill, truck accident or tank rupture and 2) chronic, long-term, low-dosage exposure. Hydrazine if directly contacted can cause burns to the skin, eyes and is highly irritating to the mucous membranes. The products Material Safety Data Sheet and label as required by the OSHA Hazard Communications standard should be consulted for the most up-to-date and complete information on health hazards.

Even though hydrazine can be absorbed into the body in toxic amounts by either acute or chronic exposure, employee exposure to hydrazine can be minimized by simple and effective engineering controls, supplemented by mandatory use of protective equipment and proper handling procedures. What can be done to prevent exposure to hydrazine? Most obviously don't drink it! Wearing of protective clothing is most important to prevent skin contact, Table II illustrates preferred clothing items. It should be noted that leather shoes are unsuitable since leather is not resistant to hydrazine thereby presenting an exposure concern. Hydrazine cannot be removed from leather thus contaminated shoes would have to be discarded. For different activities, less equipment is needed since exposure may be different when working in a storage area as opposed to the processing area. Finally, it is extremely important that the workplace be well ventilated to be certain ambient hydrazine concentrations in air will be at or below acceptable levels. If adequate ventilation cannot be provided, then further means must be adopted to provide protection against inhalation, such as using a closed handling system.

Exposure Limits

Currently there are several hydrazine exposure limits in use, of which the OSHA limit of 1 ppm is a required standard. Others such as the NIOSH (National Institute for Occupational Safety and Health) or ACGIH (American Conference of Governmental Industrial Hygienists), are only guidelines. The OSHA Standard was developed from ACGIH 1968 values. Table III illustrates these exposure limits. The ACGIH recommendation of 0.1 ppm is for 1985-1986 and is based on toxicology information gathered since the establishment of the OSHA standard.

The latest toxicological information on hydrazine is contained in the recently issued Air Force Aerospace Research Laboratory Report on the "Chronic Inhalation Toxicity of Hydrazine: Oncogenic Effects".[8] This study examined the exposure by the inhalation route and used hydrazine, the free base, rather than the sulfate salt of hydrazine as shown in Table IV.[8] These inhalation studies were performed in several species - rats, mice, hamsters and dogs - to assess the cancer producing potential of hydrazine. The inhalation exposures were conducted on a six hour/day, five days/week schedule (to simulate an industrial type of exposure) for a one year period followed by an observation period. Results of the studies indicated that hydrazine was a weak tumorigen capable of causing respiratory tumors, primarily benign (non-malignant), at the OSHA Permissible Exposure Limit (PEL) of 1 ppm.

Based on these results, the Air Force study concluded that the OSHA Permissible Exposure Limit expressed as an 8 hour time-weighted average exposure of 1.0 ppm hydrazine is unsatisfactory, while the American Conference of Governmental Industrial Hygienists (ACGIH) recommended Threshold Limit Value (TLV) of 0.1 ppm appears to be a low-risk exposure level.

Given the results of the USAF study and the ACGIH recommendation, it would appear that keeping levels of hydrazine at or below the

ACGIH recommendation of 0.1 ppm for an 8 hour day time-weighted average over a 40 hour week would provide an adequate margin of safety for the tumorigenic potential of hydrazine.

Detection of a hydrazine odor (similar to that of ammonia) indicates a vapor concentration of 3-5 ppm which is well in excess of the allowable exposure limits.[9] When ventilation or a closed handling system is not feasible or when disposing of significant spills, inhalation hazards should be controlled by protecting personnel with a self-contained breathing apparatus. Cartridge respirators are not suitable for hydrazine.

Routine air monitoring should be an integral part of any hydrazine user's employee protection program. Sensory detection of hydrazine odors at 3-5 ppm is not adequate.[9] There are a number of commercially available air monitoring instruments and detection devices listed in Table IV. This information is not necessarily all inclusive and is not meant to be a recommendation for certain commercial products but an attempt to aid hydrazine users to develop necessary personnel protection programs. In addition, there are NIOSH and Air Force approved methods for determination of hydrazine compounds in air. These procedures are based on a measured volume of air being drawn through a tube containing an acid impregnated treated packing material to chemically react with the hydrazine. The sorbent is treated to desorb the hydrazine, and the concentration of hydrazine determined colorimetrically with p-dimethylaminobenzaldehyde or gas chromatography.

Use of proper protective equipment will prevent personnel contact by any of the three routes of contact; dermal, oral or inhalation. In addition to having proper protective clothing, proper care and observance of safety and cleanliness should be observed by all workers. An important way to minimize exposure to hydrazine is by using a closed handling system, whether in a batch or continuous unloading arrangement. Nitrogen padding or blanketing should be maintained to prevent air oxidation of the hydrazine, and to raise the lower explosive limit to 38% for nitrogen-hydrazine mixtures.

Handling Accidents

From time to time, accidents not involving personnel exposure may happen such as spills or fires where hydrazine may be nearby and emergency action is clearly necessary. All spills should be immediately washed down with large volumes of water to prevent exposure and then neutralized prior to discharge. Water in large quantities is the recommended method for fighting fires involving hydrazine. A coarse spray is most effective, since it gives an immediate surface dilution effect. In addition to extinguishing the fire, a coarse water spray will cool adjacent drums and at the same time dilute the exposed solution to a less hazardous concentration, in terms of a inhalation or fire hazard. If clothing is involved, douse with water followed by immediate removal of any contaminated clothing.

Waste hydrazine from spills or process effluent presents a problem of neutralization prior to discharge. Dilute aqueous hydrazine solutions will react with the dissolved oxygen in water and will eventually consume all of the hydrazine, producing only nitrogen and water. Use of a dilute oxidizer solution will speed up the neutralization reaction. An aqueous solution (5% or less) of sodium hypochlorite or calcium hypochlorite (prepared from swimming pool dry chlorinator) or dilute hydrogen peroxide may be used as illustrated in Table V. All neutralizations must be carried out using very dilute solutions (5% or less). To insure neutralization, the discharge can be monitored for residual hydrazine using a standard boiler water test kit utilizing the p-dimethylamino benzaldehyde reagent. If an available chlorine oxidizer had been used then one could measure residual chlorine to insure neutralization. Finally hydrazine should be disposed of in a manner approved by appropriate Federal, state and local regulatory agencies.

Conclusion

Hydrazine, along with many other industrial chemicals, is classified as a hazardous material. It is reactive, the property which makes it an effective propellant, chemical intermediate and oxygen scavenger, but it is toxic. Therefore, it is necessary to protect the operator to avoid skin contact, ingestion and to provide adequate ventilation. It is also necessary to store hydrazine properly, avoid contact with heat. Like any other industrial chemical, reasonable precautions permit hydrazine to be stored, handled and dispensed safely. The successful preparation and use of hydrazine for boiler water treatment and for the government's space programs for almost 30 years is testimony to the fact that hydrazine can be handled safely on a daily basis.

TABLE I

HYDRAZINE PHYSICAL PROPERTIES

Solution Strength

Property	35%	64%	70%	AH	MMH	UDMH
Density gm/ml	1.0207	1.032	1.029	1.004	0.874	0.784
Freezing Pt. °C (°F)	-65 (-85)	-51.7 (-61)	-56 (-68.8)	2.0 (35.6)	-52.4(-62.3)	-57.2(-71)
Boiling Point °C @ 760 mmhg (F°)	1.09.4 (228.9)	120.1 (248.2)	120 (248)	113.5 (236.3)	87.5 (189.5)	63 (146)
Flash Point °F (COC)	NONE	161	150	125	70.0	5

TABLE II

PERSONNEL PROTECTION

Clothing and Equipment	Materials
Protective Suit (or apron)	Butyl Rubber
Face Shield	Plastic
Hard Hat	Plastic
Goggles	Chemical Safety Type
Gloves	Butyl Rubber
Boots	Butyl Rubber
Respirator	Self-Contained Air

TABLE III

CURRENT EXPOSURE LIMITS

		Hydrazine	MMH	UDMH
OSHA	Current Standard	1 ppm	.2 ppm	.5 ppm
NIOSH	Recommendation	0.03 ppm	.04 ppm	.06 ppm
ACGIH	Recommendation	0.1 ppm	.2 ppm	.5 ppm

TABLE IV

HYDRAZINE MONITORING EQUIPMENT & PRACTICES

Monitoring Practice	Method	Equipment
Area	Absorbtion	Bendix/Gastec
Area/Personnel	Dry Agent	MDA Scientific Glenview, IL
Area	Adsorbtion	MSA Pittsburgh, PA
Area/Personnel	Adsorbtion	National Draeger Pittsburgh, PA
Area	Electrochemical Voltammetric Sensor	Interscan Chatsworth, CA
Area/Personnel	Absortion Colorimetric Gas Chromatography	NIOSH S237 NIOSH P & CAM 248
Personnel	Colorimetric Badge	American Gas & Chem Northvale, NJ

TABLE V

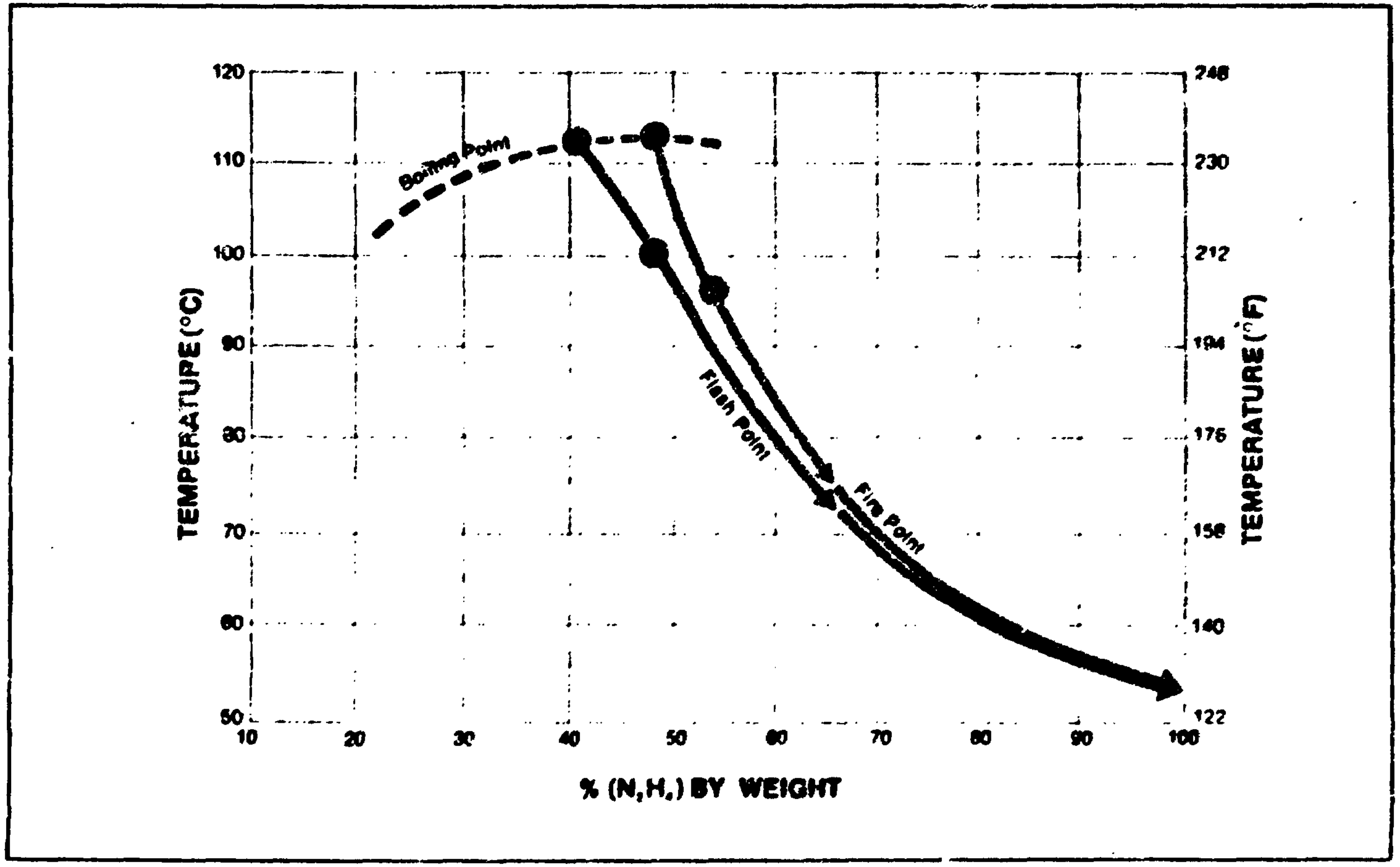
RECOMMENDED NEUTRALIZING AGENTS FOR SPILLS

The Wash Solutions should be diluted to
1- 5% N_2H_4, Prior to Neutralization

Reagent	Reaction Products	Heat Evolved KCAL/Mole N_2H_4
Water	N_2H_4 x H_2O	3.9
Cl_2	N_2, HCl	160
Calcium hypochlorite	N_2, $CaCl_2$	177
H_2O_2	NH_3, N_3H	91-121

Neutralization should be complete before waste is discharged to sewer. Follow Local and Federal Regulations concerning liquid discharges from your plant site.

FIGURE I



Open Cup Flash & Fire Points For
Aqueous Hydrazine Solutions Using
ASTM Open Cup Method (D92-46)
With A Glass Cup

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(9) K. H. Jacobson et al., A.M.A. Arch. Ind. Hlth, 12, 609-616, (1955)

SOLID ROCKET BOOSTER COMMAND DESTRUCT SYSTEM HAZARD STUDY

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ABSTRACT

Since the original hazard studies were performed for NASA, there have been significant changes both in the Solid Rocket Booster (SRB) and in the Command Destruct System. Specifically, ~~a~~ new case material, filament wound graphite, will be utilized on certain launches. The Linear Shaped Charge (LSC) of the destruct system has also been changed from 750 grains/foot HMX with an aluminum liner to 1000 grains/foot HMX with a copper liner. Because of these changes, NASA requested the Naval Surface Weapons Center (NSWC) to determine experimentally the effects of the Command Destruct LSC on the SRB case/propellant. This paper will summarize the various work elements and their specific findings.

The LSC activation tests did not produce a detonation of the propellant on any of the tests. ~~Moreover,~~ the most severe reaction was a rather mild burning with no propellant yield. The material response studies indicated that the formation of a porous bed was highly unlikely. The Shock Sensitivity/Detonability Studies indicated that direct shock initiation of detonation by the LSC is impossible~~; moreover,~~ they indicated that a Deflagration-to-Detonation Transition (DDT) would not occur. Based on the results of the study, the conclusion was that activation of the Command Destruct LSC would not cause a detonation of the SRB propellant. At most, a rapid burn is expected.

BACKGROUND

The Command Destruct System on the Solid Rocket Booster (SRB) of the Space Shuttle utilizes a Linear Shaped Charge (LSC) located in a cable tray running approximately 75% of the length of the SRB. Upon activation, the LSC is supposed to cut open the SRB case to terminate thrust without producing a major reaction in the SRB propellant.

The Naval Surface Weapons Center (NSWC) performed and documented the original hazard analysis for contingency aborts of the space shuttle using the range safety Command Destruct System.[1,2] Since the publication of these studies, there have been several, possibly significant, changes in the SRB and in the Command Destruct System itself. Specifically, the SRB case material was changed from D6AC steel to either D6AC steel or filament wound graphite and the LSC from 750 grains/foot HMX with an aluminum liner to 1000 grains/foot HMX with a copper liner. For reference purposes, the Solid Rocket Booster propellant is a composite material designated TP-H1148, manufactured by Morton Thiokol.

Because of the changes, it was felt that an experimental determination of the effects of the Command Destruct LSC on the SRB case/propellant should be performed. The estimated critical diameter for the SRB propellant is on the order of several feet. Testing with charges of this size was not within the scope of this effort. Instead, investigations of specimens with dimensions below the critical diameter were planned and conducted.

The program had as its goal the determination of the type and severity of reaction caused by the Command Destruct Linear Shaped Charge on the Solid Rocket Booster propellant. All of the testing, both in the field and in the laboratory, has been directed to this end.

The experimental effort was incorporated into a program entitled "Solid Rocket Booster Hazard Study--Revised Phase I." This effort had the following work elements:

(1) Linear Shaped Charge Performance Tests
    (a) LSC/Propellant Slab Tests
    (b) LSC/Propellant-filled Cylinders

(2) Material Response
    (a) Uniaxial High Strain Rate Tests
    (b) Characterization of Damaged Propellant
    (c) Characterization of Propellant Simulant

(3) Structural Response
    (a) Fragmentation Evaluation of Filament Wound Case Solid Rocket Booster
    (b) Airblast Re-evaluation (if required)

(4) Detonability/Shock Sensitivity Studies
    (a) Large Scale Gap Tests
    (b) Aquarium Tests
    (c) Granular Bed Tests
    (d) LSC/Inert Propellant Simulant Tests

(5) Final Report

Elements (1) and (2)--Linear Shaped Charge Performance Tests and Material Response will be discussed in this paper. Element 4--Detonability/Shock Sensitivity Studies is the subject of a separate paper at this symposium. Each of the work elements will be covered in detail in a series of NSWC Technical Reports to be published shortly. These are summarized in Table 1.

TABLE 1 REPORT SUMMARY

Element Number	NSWC TR Number	Title	Author
1	85-62*	Space Shuttle Command Destruct System/Solid Rocket Booster Propellant Interaction	Swisdak & Peckham
	85-346	Solid Rocket Booster Command Destruct System Hazard Study: Volume 2, Propellant Cylinders	Peckham
2	85-350	Solid Rocket Booster Command Destruct System Hazard Study: Volume 4, Mechanical Properties	Bazil
3	85-352	Solid Rocket Booster Command Destruct System Hazard Study: Volume 5, Fragmentation	Hinckley
4	85-348	Solid Rocket Booster Command Destruct System Hazard Study: Volume 3, Shock Initiation Studies	Tasker
5	85-344	Solid Rocket Booster Command Destruct System Hazard Study: Volume 1, Summary	Swisdak

* Published 21 January 1985; all others to be published

LINEAR SHAPED CHARGE PERFORMANCE TESTS

The purpose of these tests was to determine if the activation of the LSC would cause significant propellant reaction (in this scale of tests). Two series of tests were conducted: Series I, utilizing propellant slabs weighing approximately 90 pounds and Series II utilizing propellant cylinders containing approximately 20 pounds of propellant. The Series I tests had actual case material (either steel or filament wound graphite) bonded to one surface. The Series II tests utilized cylinders of both case materials.

At the start of this testing, it was felt that if a violent reaction occurred during the testing of these sub-critical diameter specimens, then a reaction of at least comparable violence would be expected at full scale. If no reaction, or a mild reaction occurred, it did not, necessarily, mean that such a mild reaction would be expected in the full scale (though this later was shown by Tasker[3] to be the case).

LSC Description. The LSC used on the Shuttle is Jet Cord Model HC-1000-J. This contains 1000 grains per foot of HMX in a copper liner. Figure 1 is a sketch of a sample of the LSC. The spacing between the LSC and the SRB case is specified to be between 1.00 and 1.20 inches for the steel case and 0.85 to 1.35 inches for the filament wound case.

Shuttle-type LSC material was used in all tests. LSC retainer brackets were used to maintain a 1.1-inch spacing between the LSC and all target materials.

Propellant Slab Description. The Series I SRB case/propellant specimens were slabs (sandwiches) of case/liner/propellant with nominal dimensions of 24" x 7" x 12" (L x W x T). The nominal propellant weight was 90 pounds. The propellant used for all of these tests was a composite material, TP-H1148, manufactured by Morton Thiokol Inc. Two case materials were utilized: (1) D6AC steel, 0.48" thick and (2) filament wound graphite, 1.14" thick. Both case thicknesses are representative of what either is flying (steel case), or will be flying (filament wound case), on the SRB. Figure 2 is a sketch of both types of samples. Figure 3 shows photographs of one of the slabs prior to firing.

Propellant Cylinder Description. The Series II specimens were cylinders of case/liner material filled with propellant. The cylinder internal diameter (propellant diameter) was 6.0 inches in each case. The cylindrical wall thickness was either 0.48" of D6AC steel or 1.14" of filament wound graphite. Each cylinder was 14.0 inches long and contained approximately 20 pounds of material. End closures were formed from 1/4-inch aluminum plates held together with threaded-rod. Figure 4 shows sketches of both types of cylinders. Figure 5 shows photographs of one of the cylinders prior to firing.

Test Results--Series I. The LSC functioned as designed and clearly cut each case. The LSC jet did not penetrate the full 12-inch depth of the slab (no exit evidence in the high speed photography). No spalling, other than at the corners, was observed during any of these tests. The jet penetration did cause spalling at the rear face corners of the samples.

The LSC activation appeared to cause no significant, prompt propellant reaction. Pieces of both burning propellant as well as un-ignited propellant were thrown several hundred feet. The bulk of the propellant slab appeared to remain intact and was thrown between 30 and 80 feet to the rear, where it landed and burned. The location of these impact areas was consistent from shot to shot.

The high-speed photography showed the bulk of the propellant slab being translated at 60 to 80 feet per second on each shot. These velocities are consistent with the location of the impact areas.

Figure 6 is a sample of the case material remaining after a Series I test.

Detailed pressure-time data were recorded on each test. Based on this data as well as the evidence from high speed photography, there was nothing to indicate any propellant yield (i.e., the only airblast pressure was that produced by the LSC, itself).

Test Results--Series II. The Series II tests were designed to investigate the effects of geometry and mild confinement on the LSC-propellant interaction. It was felt that the change to a cylindrical geometry, which more closely modeled the real world, might produce a different reaction than that observed on the Series I tests.

The results were similar to those obtained during the Series I tests. The LSC activation produced burning in the propellant. It also appeared to pressurize the cases which had the effect of blowing off the end plates. On two of the tests, the burning appeared to be of an oscillatory nature; i.e., the intensity of the burning was varying with time. The airblast instrumentation recorded nothing which could not be attributed to the LSC itself--i.e., no measurable increase in pressure. Hence, no propellant contribution.

Figure 7 is a sample of the case material remaining after a Series II test.

Again, based on all the available evidence, the LSC produced no yield from the propellant.

MATERIAL RESPONSE

The testing of the live SRB propellant was performed at strain rates of 0.7407, 7.407, 74.07, and 740.7 inches/inch/minute at 77°F. Two samples were tested at each strain rate; prior and subsequent to the testing, routine dimensional checks and sample weighings were also performed. The reason for this was to detect friability through the loss of material under test.

Table 2 gives the test data generated by the 77°F tests. A follow-on test (Table 3) was performed at -65°F to see whether the material would be friable below the glass transition temperature of the propellant. The results of the weighings showed no discernable change in weight of the live propellant, regardless of the test conditions. This indicates that the propellant remained bonded and would probably not form a bed necessary for the propagation of a DDT reaction. Figures 8 and 9 reflect the change in rupture modulus as a function of load rate and temperature. While the low temperature (-65°F) condition revealed the expected high rupture modulus, the propellant still did not undergo brittle failure.

Mechanical testing was also performed on an inert SRB propellant simulant, designated H-18 (supplied by Thiokol). The mechanical characteristics of this material are given in Table 4. A comparison of the live versus the inert rupture modulus is given in Figure 10. As can be seen, the inert material is softer and hence less susceptible to friability. This corroborates the data generated by Thiokol regarding the critical impact velocity shown in Figure 11.

MORPHOLOGY STUDIES

Propellant fragments which were retrieved after the Series I LSC tests were microscopically studied in order to determine their morphological characteristics.

Stereomicroscopical analyses indicated that a majority of the propellant fragments did not show any indication of melted oxidizer particles. However, the oxidizer particles in most of the fragments were fractured to a depth of at least three centimeters. The phenomenon suggests severe compression of the crystalline ingredients due to a reaction which was caused either by initiation of the LSC, by impact of the fragments to the ground, or by a combination of both mechanisms. There is insufficient evidence to establish the true cause.

SUMMARY

The Solid Rocket Booster Hazard Study has been a parallel effort whose goal was the determination of the effect of the Command Destruct LSC on the SRB propellant.

Based on testing of propellant/case slabs weighing about 90 pounds and propellant/case cylinders weighing about 20 pounds, the activation of the LSC produces no undesired effect. It opens the case and causes the propellant to burn. It does not cause prompt detonation.

The material properties of the shuttle propellant indicate that it is not likely to form a porous bed.

The question remained, however, that there might be a chain of events which could lead to a delayed detonation. This was addressed by Tasker in his portion of the study, which will be reported in a subsequent paper.

When Tasker's results are included, the following conclusions can be drawn:

Based on the mechanical testing and the propellant slab tests, LSC action does not appear to be able to form the necessary porous bed. Moreover, the LSC/propellant slab tests indicated that any induced burning does not accelerate. The laboratory testing has shown that the p^2t stimulus generated by the LSC is too low to detonate the porous bed. Since the porous bed cannot detonate, neither can the solid, undamaged propellant (under the same stimulus). Thus the chain is broken in several places, leading to the following conclusion:

> The action of the Command Destruct Linear Shaped Charge on the SRB propellant is highly unlikely to cause a propellant detonation. The most likely occurrence is a mild pressure burst in which the region of damage adjacent to the LSC will burn rapidly. The bulk of the undamaged propellant will, then, burn slowly.

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1. Hinckley, W. M., Lehto, D. L., Coleburn, N. L., Gorechlad, A. J., Ward, J. M., Petes, J., "Space Shuttle Range Safety Command Destruct System Analysis and Verification, Phase I - Destruct System Analysis and Verification, Phase II - Ordnance Options for a Space Shuttle Range Safety Command Destruct System, Phase III - Breakup of Space Shuttle Cluster via Range Safety Command Destruct System," NSWC TR 80-417, Mar 81.

2. Coleburn, N. L. and Zimet, E., "The Behavior of Range Safety System Ordnance for the Space Shuttle with Simulated Aerodynamic Heating," NSWC TR 81-175, 20 Oct 81.

TABLE 2. MECHANICAL CHARACTERISTICS OF SRB PROPELLANT
(77°F TEST TEMPERATURE)

STRAIN RATE RATE (IN/IN/MIN)	STRESS MAXIMUM (PSI)	ELONGATION MAXIMUM (%)	STRESS RUPTURE (PSI)	ELONGATION RUPTURE (%)	RUPTURE MODULUS (PSI)
.7407	118.9	36.0	103.8	44.4	233.8
	114.0	32.8	98.9	42.4	233.3
7.407	149.4	42.4	133.5	48.2	276.9
	147.4	38.4	125.4	50.5	248.3
74.07	203.9	45.6	189.7	57.0	332.8
	206.9	40.8	180.9	56.9	317.9
740.7	293.6	69.1	286.7	77.8	368.5
	294.2	56.2	273.5	71.0	385.2

TABLE 3. MECHANICAL CHARACTERISTICS OF SRB PROPELLANT
–65°F TEST TEMPERATURE
STRAIN RATE 74.07 IN/IN/MIN

STRESS MAXIMUM (PSI)	ELONGATION MAXIMUM (%)	STRESS RUPTURE (PSI)	ELONGATION RUPTURE (%)	RUPTURE MODULUS (PSI)
2085.7	3.2	2085.7	3.2	65178.1

TABLE 4. MECHANICAL CHARACTERISTICS OF H-18 INERT

STRAIN RATE RATE (IN/IN/MIN)	STRESS MAXIMUM (PSI)	ELONGATION MAXIMUM (%)	STRESS RUPTURE (PSI)	ELONGATION RUPTURE (%)	RUPTURE MODULUS (PSI)
.7407	74.6	35.9	62.2	56.6	113.9
	70.1	29.6	54.8	50.3	109.0
7.407	104.5	41.5	88.2	56.8	157.2
	109.0	42.2	90.1	61.7	145.0
74.07	158.3	47.4	126.7	68.6	184.7
	148.3	47.2	120.1	66.9	179.5
740.7	235.3	54.3	212.4	77.8	273.0
	225.6	59.3	195.2	84.0	232.4

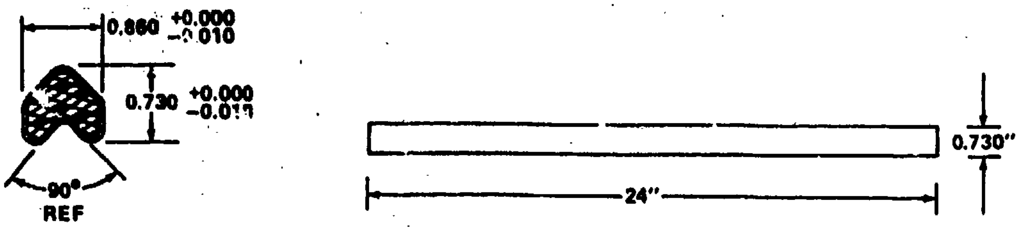
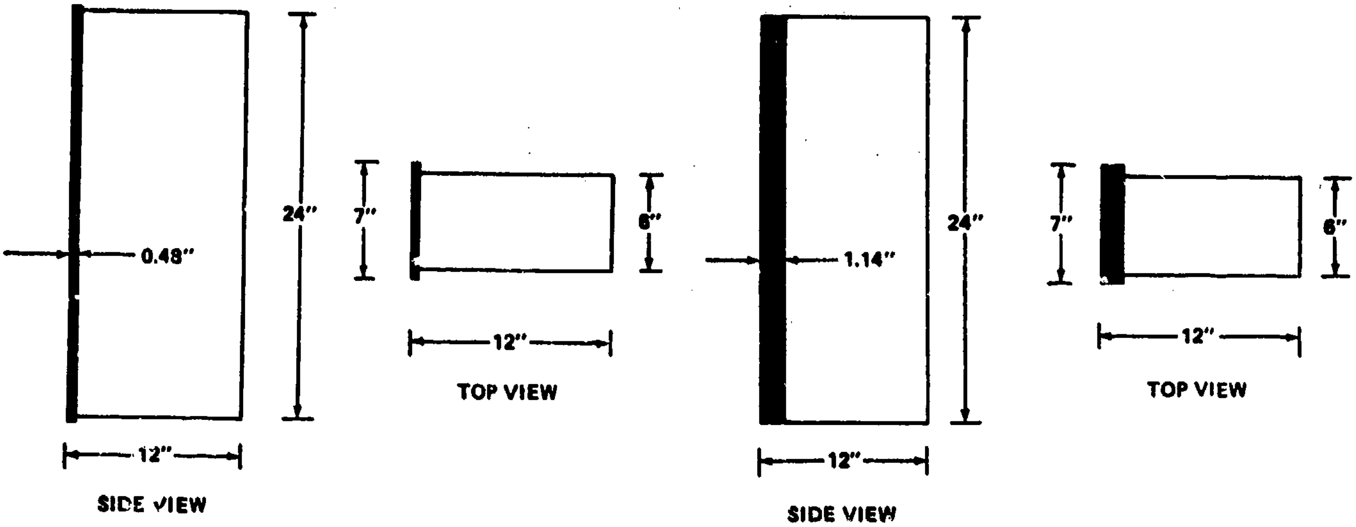


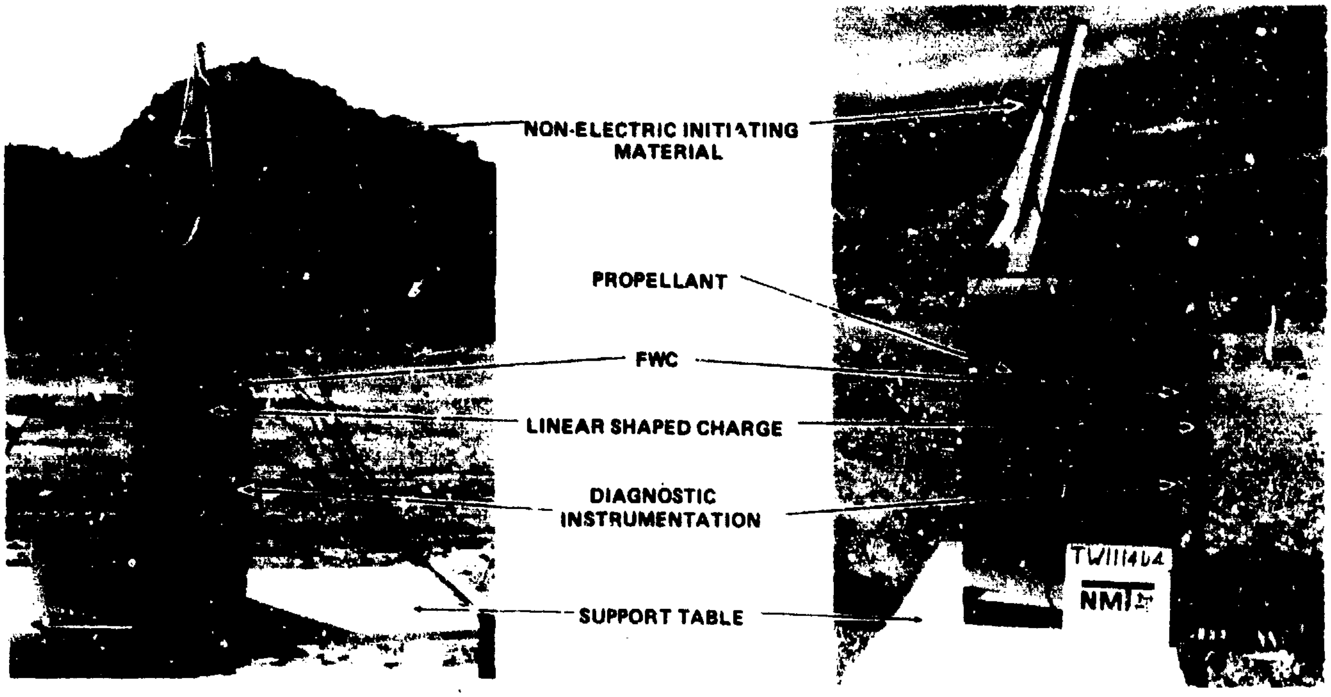
FIGURE 1. LINEAR SHAPED CHARGED DIMENSIONS



(a) STEEL CASE PROPELLANT SAMPLE

(b) FILAMENT WOUND CASE PROPELLANT SAMPLE

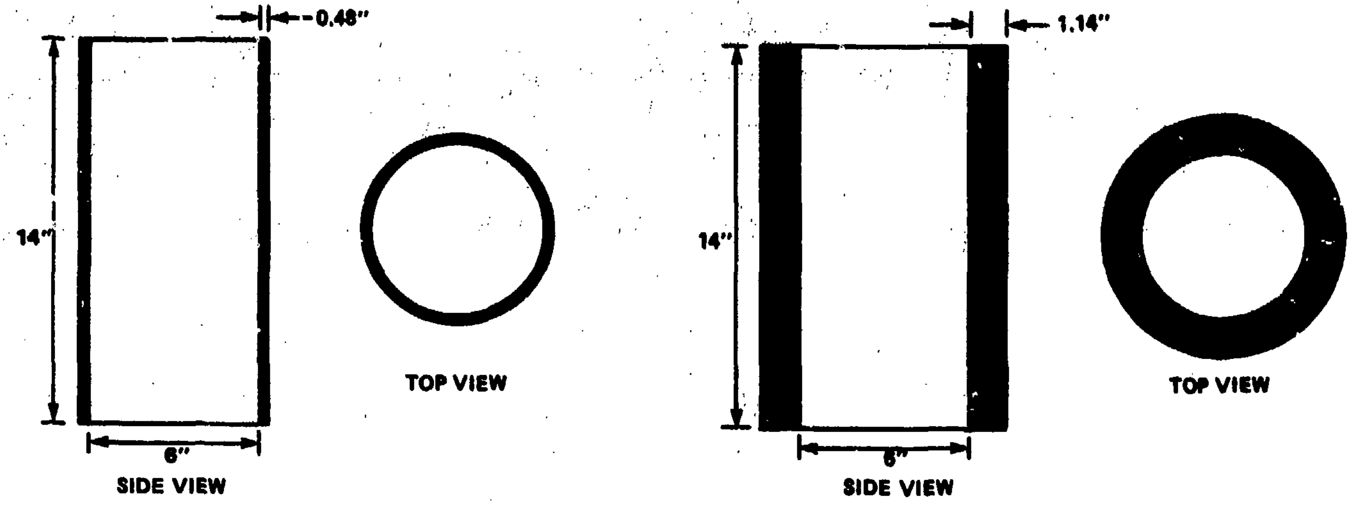
FIGURE 2. SAMPLE DIMENSIONS



FRONT VIEW

SIDE VIEW

FIGURE 3. SLAB PRIOR TO FIRING



(A) STEEL CASED CYLINDER/PROPELLANT SAMPLE

(B) FILAMENT WOUND GRAPHITE CYLINDER:PROPELLANT SAMPLE

FIGURE 4. CYLINDRICAL SAMPLE DIMENSIONS

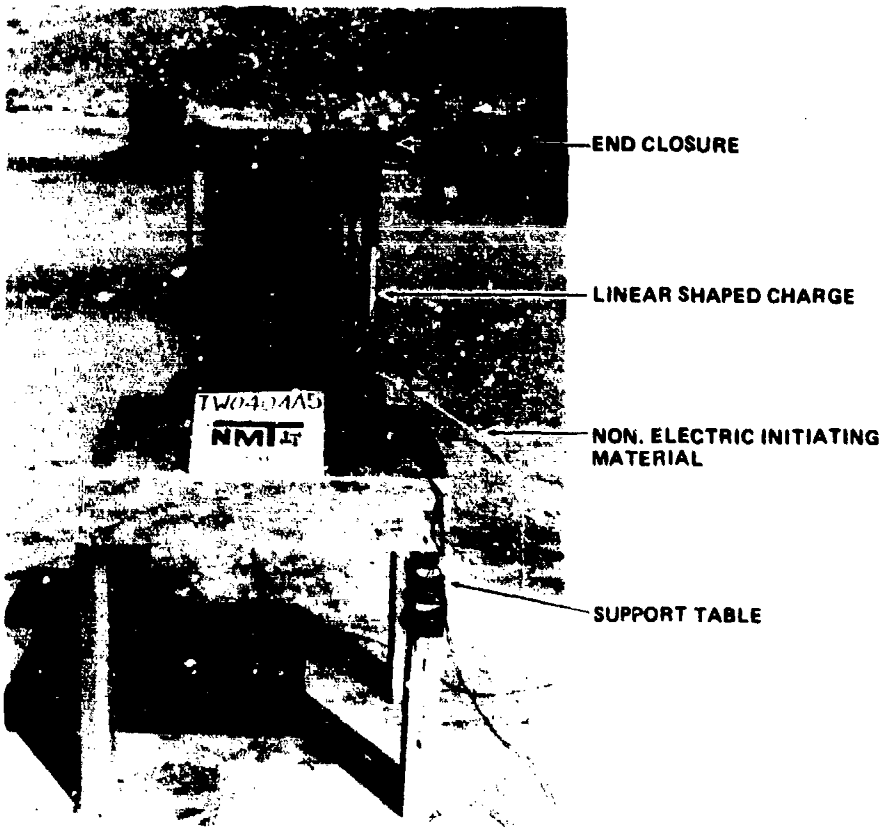
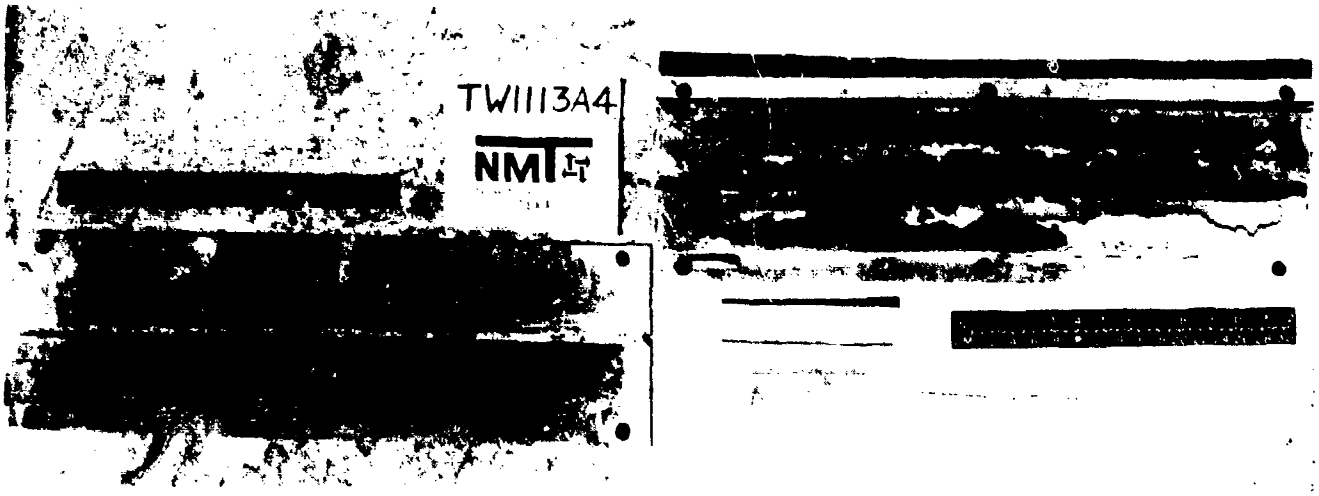
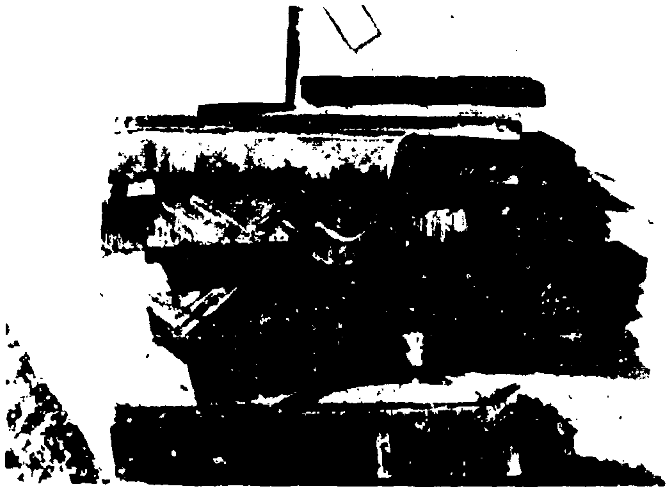


FIGURE 5. CYLINDER PRIOR TO FIRING

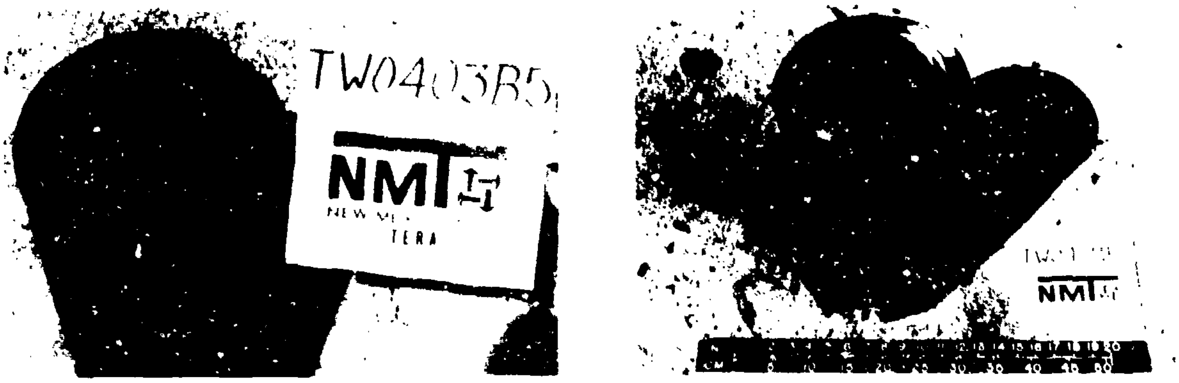


STEEL CASE



FILAMENT WOUND CASE

FIGURE 6. LSC CUTS OF SRB CASES: SERIES I



STEEL CASE

FILAMENT WOUND CASE

FIGURE 7. POST-SHOT SERIES II

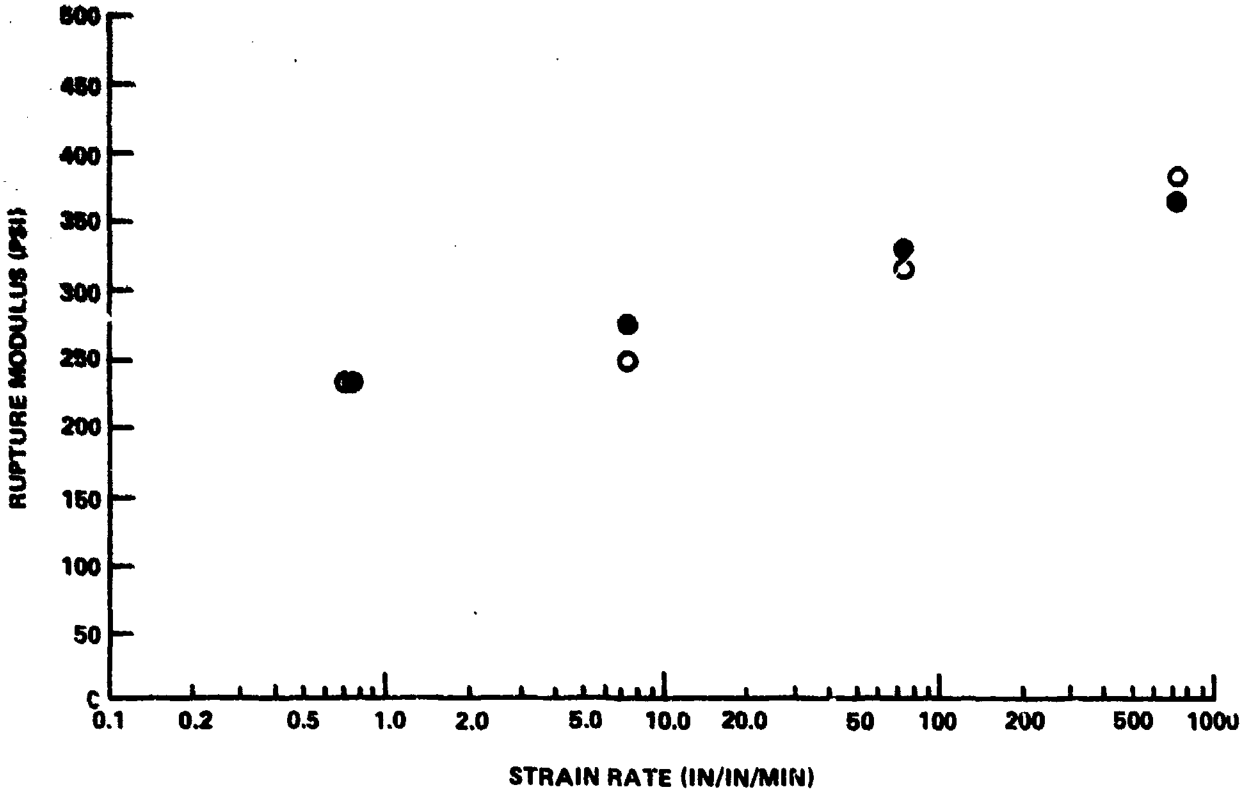


FIGURE 8. RUPTURE MODULUS VS. STRAIN RATE (SHUTTLE BOOSTER PROPELLANT)

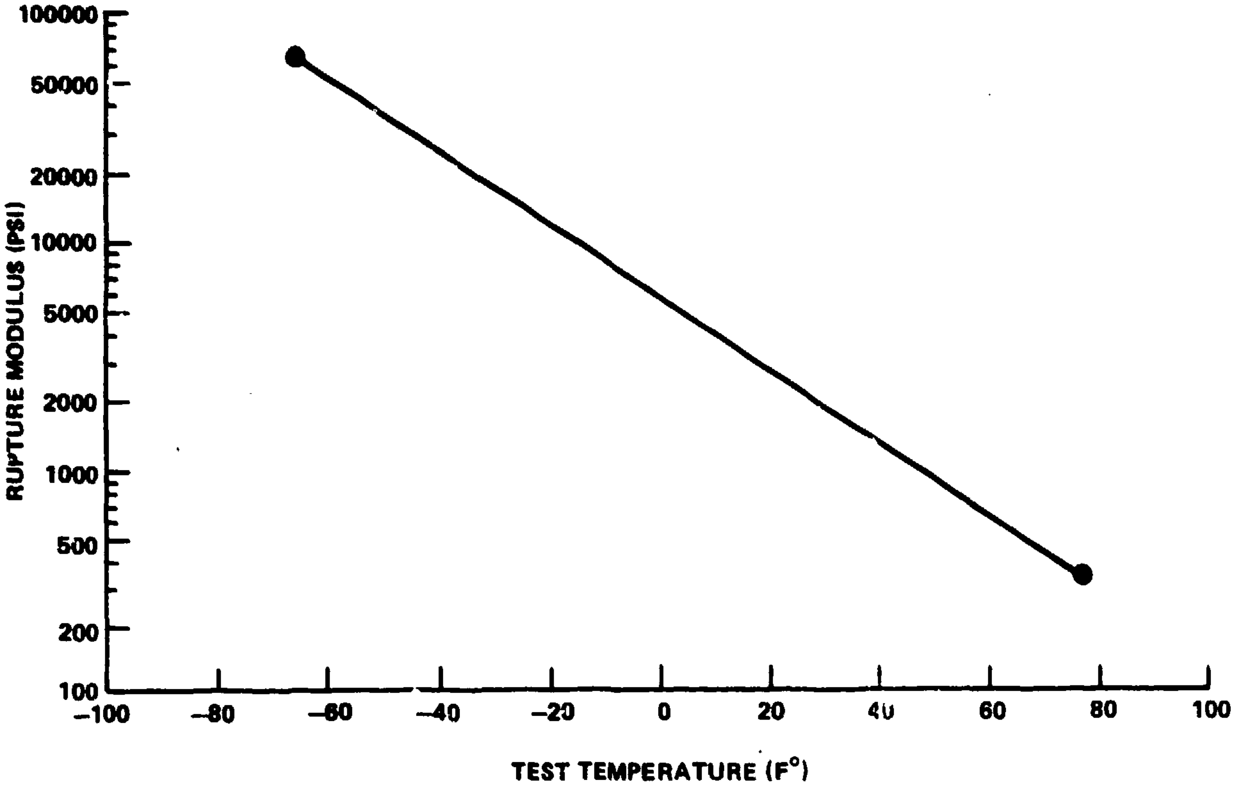


FIGURE 9. RUPTURE MODULUS VS. TEST TEMPERATURE (SHUTTLE BOOSTER PROPELLANT)

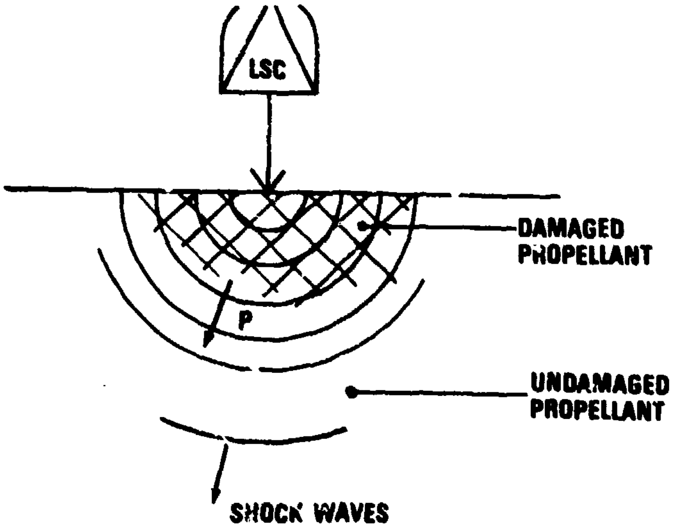


FIGURE 1. DAMAGE AND DETONATION BY LSC

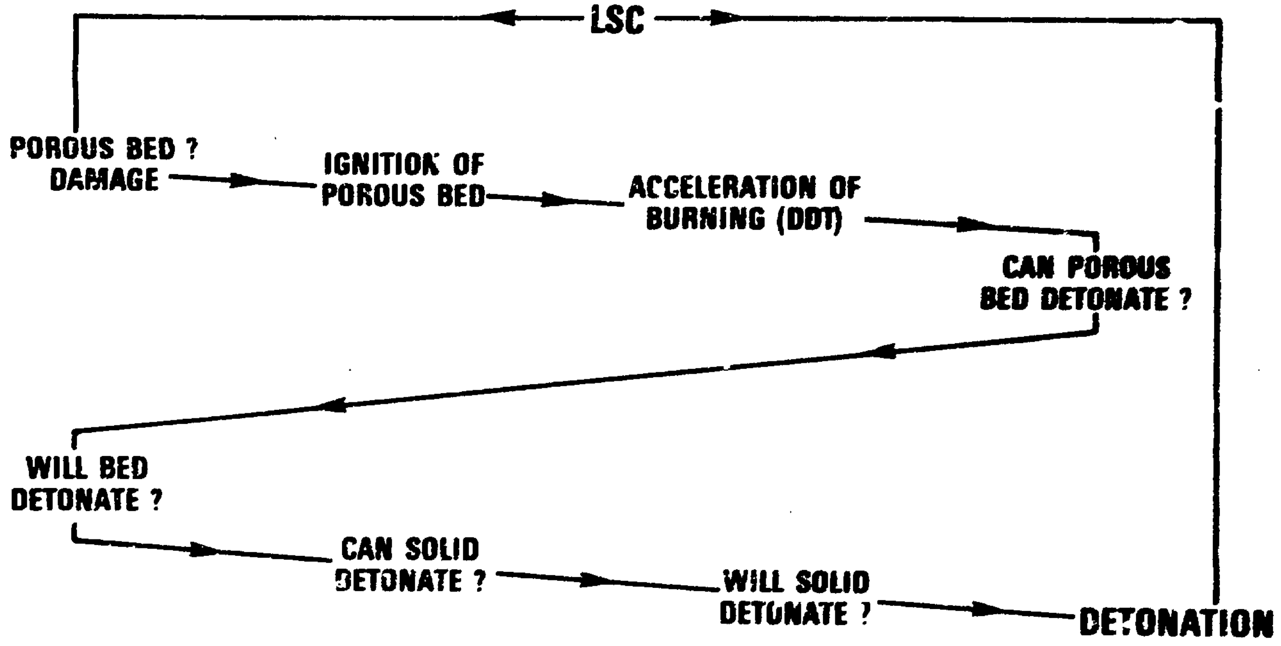


FIGURE 2. NECESSARY STEPS TOWARD DETONATION

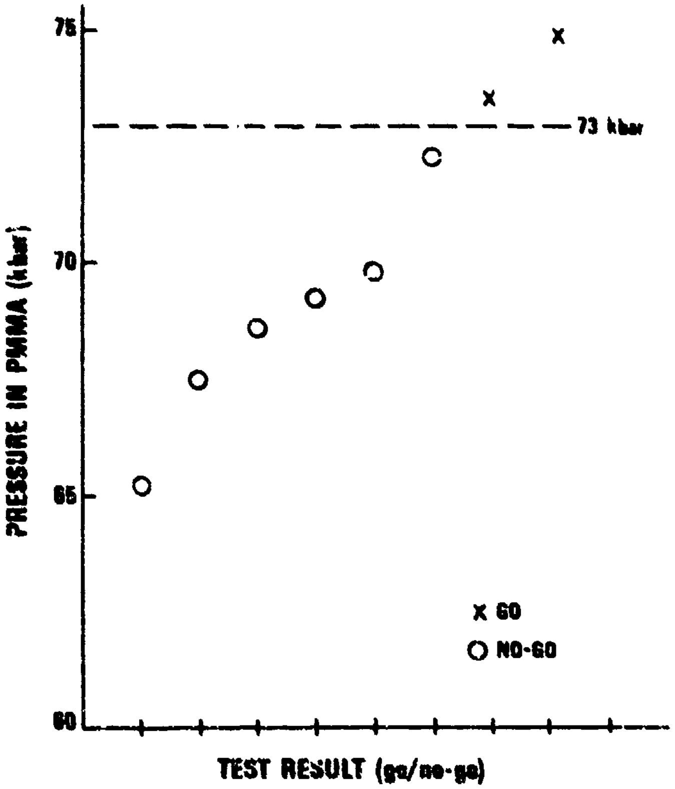


FIGURE 4. LARGE-SCALE GAP TEST RESULTS,
85 PERCENT TMD

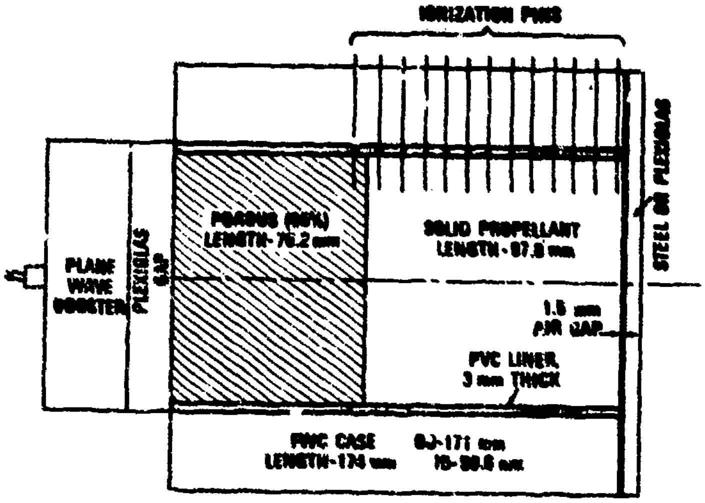


FIGURE 5. MODEL FWC EXPERIMENT

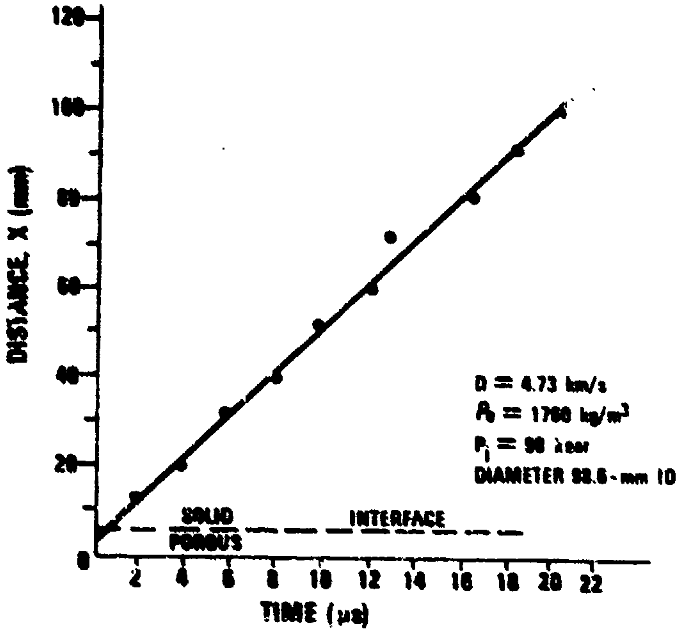


FIGURE 6. POROUS TO SOLID DETONATION

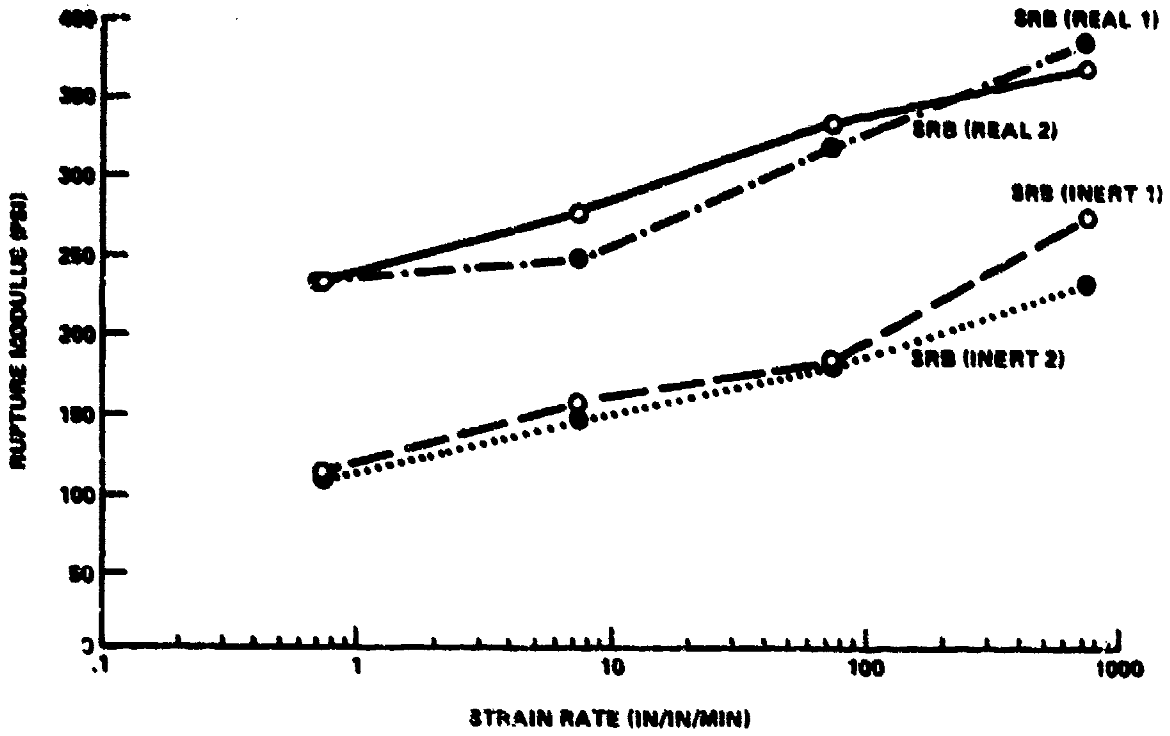


FIGURE 10. SRB RUPTURE MODULUS VS. STRAIN RATE (INERT AND REAL PROPELLANT 77°F)

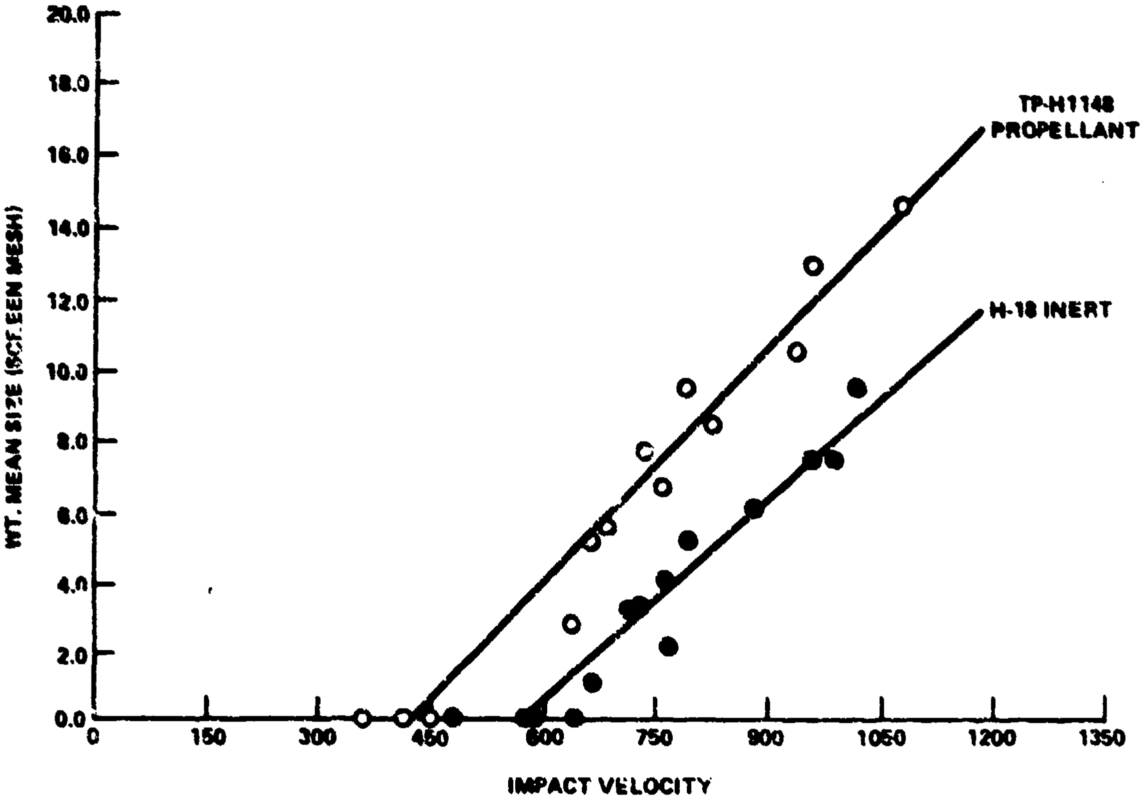


FIGURE 11. TP-H1148 PROPELLANT VS. H-18 INERT PROPELLANT
18MM SHOTGUN FRIABILITY TEST
WT. MEAN PARTICLE SIZE VS. IMPACT VELOCITY

SHOCK INITIATION STUDIES OF THE NASA SOLID ROCKET BOOSTER ABORT SYSTEM

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ABSTRACT

A series of tests has been performed in order to estimate the likelihood of a violent, destructive event occurring when the NASA Space Shuttle Solid Rocket Booster (SRB) abort system is deployed. The system utilizes a linear shaped charge to cut open the rocket motor casing. A complete analysis of the physical processes that occur between initiation of the linear shaped charge and reaction of the propellant ~~was not possible. Such a study was beyond the~~ scope of the program and also exceeded the current understanding of shock to detonation mechanisms in propellants. However, a series of minimum requirements or criteria have been established that are necessary for a detonation to be initiated. All the laboratory tests described here have been designed to obtain fundamental sensitivity data for the SRB propellant. These data are independent of the size of the propellant grain. This represents a new approach to the analysis of the possible hazards associated with the accidental ignition of solid rocket propellants.

INTRODUCTION

The Command Destruct System on the Solid Rocket Booster (SRB) of the space shuttle utilizes a linear shaped charge (LSC) located in a cable tray which runs approximately 75 percent of the length of the SRB. Upon activation, the LSC is supposed to cut open the SRB case to terminate thrust without producing a major reaction in the SRB propellant.

The Naval Surface Weapons Center performed and documented the original hazard analysis for contingency aborts of the space shuttle using the range safety Command Destruct System[1]. Since the publication of these studies, there have been several changes in the SRB and in the Command Destruct System itself. Specifically, the SRB case material was changed from D6AC steel, 12.2mm thick, to filament wound graphite, 25mm thick, and the LSC from 750 grains/foot HMX with an aluminum liner to 1000 grains/foot (213 g/m) HMX with a copper liner jet cord model HC-1000-J. The Solid Rocket Booster propellant is a composite material designated TP-H1148, manufactured by Morton Thiokol, 69.6% ammonium perchlorate, 16% aluminum and 14% PBAN (Polybutadiene Acrylonitrile Terpolymer).

Because of these changes, it was felt that an experimental determination of the effects of the command destruct LSC on the SRB case/propellant should be performed. The estimated critical diameter for the SRB propellant is on the order of meters. Testing with charges of this size is not within the scope of this effort. Instead, investigations of specimens with dimensions below the critical diameter have been conducted.

A series of minimum requirements, or criteria, were established that are necessary for a detonation to be initiated. If these criteria are not met, then detonation is not possible.

INITIATION CRITERIA

When the LSC of the space shuttle abort system is fired and the jet of copper penetrates the case, the initial jet velocity is circa 2 km/s. The jet subsequently generates a shock wave in the solid propellant and will eventually shatter the propellant bed if detonation does not occur.

The first question is then:

(1) Will the LSC-induced shock wave promptly detonate the solid propellant?

This is the only direct path to detonation. The alternative route is via a sequence of steps. Each condition or step must be satisfied.

If detonation is not induced, then the shattered propellant could be induced to burn; hence the second criterion is:

(2) Will the LSC cause the shattered, porous propellant bed to burn?

Note that prompt LSC shock initiation of the porous bed is discounted, the jet-induced shock wave preceeds the shattering of the propellant, therefore the shock travels through undamaged propellant; shattering occurs behind the shock wave in its wake when reflections produce tensile stresses (See Figure 1).

(3) If burning has been induced, will this burning accelerate?

If the burning accelerates, then the next concern is whether the porous bed will undergo a burning-to-detonation or deflagration-to-detonation transition (DDT).

(4) Is a deflagration-to-detonation transition (DDT) process possible?

To answer criterion (4), we must consider whether it is possible to detonate the porous or solid propellant under any conditions. The following questions must then be answered:

(5) Can the porous bed sustain a detonation?

(6) Can the undamaged propellant sustain a detonation?

(7) Will the porous bed detonate?

(8) Will the solid undamaged propellant detonate?

(9) Can the detonating, damaged propellant initiate detonation in the solid propellant?

The sequences of events or pathways towards possible detonation are shown in Figure 2.

CRITICAL ENERGY FLUENCE

The shock sensitivity of the damaged and undamaged propellant must be determined for the various sequences of events between deployment of the LSC and final detonation. To this end the "$p^2\tau$" criterion, first proposed by Walker and Wasley,[2] has been invoked. The "$p^2\tau$" criterion is used to determine the shock stimulus necessary to initiate detonation in an energetic material. If p is the shock pressure, τ the equivalent time duration of the shock, E_c the critical energy fluence and Z the shock impedance of the material that supports the shock then the criterion is usually expressed thus,

$$\frac{p^2\tau}{Z} = E_c$$

This has been extended beyond its original purpose to provide the critical stimuli required for deflagration as well as for detonation; other work has shown that this is a valid technique.[3] The $p^2\tau$ criterion is used here as an engineering guide, it is an extremely useful tool for the estimation of the shock sensitivity of an energetic material but should be used with caution. This is because in studies such as the one reported here the pressures and time durations are not known with sufficient accuracy for an exact $p^2\tau$ criteria to be established. To be safe the shock energy of any stimulus must be determined to be significantly less than the critical energy E_c required for initiation of a deflagration or detonation. To avoid ambiguity the $p^2\tau$ results are quoted here in units of kbar^2 μsec and not in terms of energy fluence per unit area.

THE MEASUREMENT OF THE LSC SHOCK STIMULUS

Experiments were performed in which the initial shock pressure generated by penetration of the SRB casing by the linear shaped charge jet was measured. The jet was allowed to penetrate either water or PMMA (Plexiglas) targets. The shock wave velocity U_s was obtained using high speed streak photography. From this velocity the shock wave pressures could be obtained.

From the laws of conservation of momentum and mass, it can be shown that:

$$p = \rho_0 U_p U_s \qquad (1)$$

where ρ_0 is the initial density and U_p the particle velocity. In the absence of other data the shock hugoniot data for FFP propellant was used[4] to obtain the particle velocity.

The SRB propellant is Morton-Thiokol TP-H1148 with 69.6% AP (Ammonium Perchlorate), 16% Al and 14% PBAN (Polybutadiene Acrylonitrile Terpolylmer) and has a theoretical maximum density of 1.774 kg/m^3. The shock hugoniot data for the two are unlikely to be identical but are believed to be close enough to obtain order of magnitude estimates.

Hence the expression,

$$U_s = 1.327 + 2.43\, U_p \ \text{km/s} \qquad (2)$$

was obtained for FFP and this was combined with equation 1 to obtain pressure. Corrections were made to the calculated pressure for the differences between the shock hugoniots of the propellant and the PMMA or water using the conventional impedance mismatch technique, see Table I.The shock pressure was found to be a maximum of p = 40 kbars (4GPa). The shock duration could not be directly measured in these experiments; it can only be estimated to be less than 1 µs, i.e. $\tau < 1$ µs.

The $p^2\tau$ criterion was used as an engineering guide to determine whether or not detonation was possible. For p = 40 kbars, $\tau < 1$ µs, we have $p^2\tau < 1600$ kbar^2 µs. It will be shown later from Aquarium test data that this stimulus is not sufficient to initiate prompt detonation; i.e., $p^2\tau > 6300$ is required for even low order burning.

TABLE I
LSC SHOCK WAVE PARAMETERS

Test No.	Target Material	LSC Standoff Air (in)	LSC Jet Fragment Velocity (m/sec)	Initial Shock Velocity (m/sec)	Initial Particle Velocity (m/sec)	Transmitted Pressure (kbar)
1	Water	0	1880	3290	1030	40
2	Water	0	1802	3110	850	32
3	Plexiglas	0	-	3400	560	29
4	Plexiglas	1.10	3065	3610	650	31

SHOCK SENSITIVITY TO DEFLAGRATION OR DETONATION

UNDERWATER SHOCK SENSITIVITY MEASUREMENTS; THE AQUARIUM TEST

To determine the shock sensitivity to deflagration or detonation the NSWC Aquarium test was used, Liddiard.[5] In this test, cylindrical samples of the propellant are suspended in water and subjected to precisely controlled shock waves of known pressure and time duration. The samples were protected with a thin coating of silicone water repellant. The response of these samples is monitored by high speed framing cameras operating at speeds of circa 10^6 frames per second. An exhaustive study was not undertaken; further work would be required to extend the study to the effects at very high pressure. However, the results obtained are sufficient for the analysis of the initiation criteria described above.

RESULTS

The pressures transmitted to the propellant have been estimated by use of the impedance mismatch technique based on hugoniot data for FFP propellant. Time durations were estimated from computer code modelling of the test.

TABLE II

p (kbars)	τ (μs)	$p^2\tau$ (kbar^2 - μs)	Response
7.0	30	1470	Very slight damage; no burning, no deflagration or detonation.
14.5	30	6300	Slight burning; no deflagration or detonation.

CONCLUSIONS

From these results, we can assess that, for any size charge, no deflagration (let alone detonation can be induced for stimuli of less than 6300 (kbar)^2 μsec. Clearly criterion (1) cannot be satisfied. The initiation of prompt detonation by the LSC is impossible.

SHOCK SENSITIVITY AND CRITICALITY DATA FOR THE DAMAGED PROPELLANT

BACKGROUND

In order to answer the questions of criteria (4) and (5), we must establish whether the porous propellant can detonate and, if so, what limitations are there on the detonation process.

It has long been known that porous propellants containing Ammonium Perchlorate (AP) and Aluminum can detonate, Price.[6] However, solid propellants (of zero or low porosity) do not readily sustain detonation, although pseudo-stable detonations can be induced (see below). Experiments were therefore designed to determine how high the porosity must be (or how low the density) for a stable detonation to be sustained.

EXPERIMENTS

A modified NSWC Large Scale Gap Test (LSGT) was employed, Liddiard.[7] In this modified test, a steel tube of 47.6 mm O.D., 36.4 mm I.D., and 139.7 mm in length was filled with propellant of known porosity. The porosity was controlled by cutting the propellant into chips of 1 1/2 x 1 1/2 mm cross section and 3 mm length. The steel tube was loaded in small increments with pre-weighed quantities of these chips. The chips were pressed to a pre-determined height to obtain the desired density or porosity. Plexiglas caps were employed to keep the compressed materials in the tube; the cap adjacent to the donor was 1 mm thick and the other cap 6 mm thick. Ionization gauges were inserted into the propellant through holes in the wall of the tube. These gauges allow the progress of a detonation wave in the propellant to be monitored and its velocity obtained. The propellant was shocked by a standard donor explosive charge of pentolite (50.8 mm diameter, 50.8 mm length) placed on top of the tube. (No attenuator, or gap, other than the 1 mm cap was used, so that the propellant would always detonate if detonation were possible.) A steel witness plate was placed at the other end of the tube to provide additional evidence that a detonation did or did not occur. Should detonation occur, a hole is punched completely through the witness plate. The porosity of the propellant was varied, from experiment to experiment to determine the maximum density that would support a stable detonation in the diameter of the test. The size of the chips was held constant.

RESULTS

The results are shown in Figure 3. It is clear that a stable detonation can be induced in the propellant for densities up to at least 85% TMD theoretical maximum density (TMD) or 1510 kg/m^3 (fulfilling criteria 5 and 7). There is an apparent increase of detonation velocity with loading density; within the scatter of the experiment, the slope is not significantly distinguishable from zero at the 95% confidence level. For all densities up to and including 90% TMD a clear hole was punched in the witness plates (which is indicative of detonation). However, the ionization gauges records showed wave instabilities above 85% TMD, so that the wave would probably fail in a longer run length. Also shown is the measured detonation velocity of the 100% TMD, 100 mm test reported below.

From these results, a pressing density of 85% TMD was selected. This density provides the largest simulus when the porous bed is detonated and therefore is the most likely to initiate the solid undamaged propellant beyond the LSC damage zone.

At 85% TMD, the measured shock velocity (from the ionization gauge records) was D = 4.40 km/s. Hence using the γ-law equation of state for the detonation products

$$p = \frac{\rho_o D^2}{\gamma+1} \qquad 73 \text{ kbars.} \qquad (3)$$

This is the maximum pressure to which the solid undamaged propellant is subjected. This is also the pressure stimulus to which the damaged propellant is subjected and must therefore be sufficient to initiate and sustain detonation in the 85% TMD bed (see below).

SHOCK SENSITIVITY OF DAMAGED PROPELLANT

It is well known that the sensitivity of propellants or explosives, to the initiation of burning, deflagration or detonation, is greatly enhanced by the presence of voids, flaws, defects, or dislocations within the matrix. A perfect, flawless energetic materials, should it exist, would be extremely difficult to initiate. For this reason the porous propellant (85% TMD) is significantly more sensitive than the propellant in the undamaged state. Clearly the sensitivity of this porous propellant can be treated as a worst case. If it can be demonstrated that the porous bed will not detonate, then the undamaged propellant cannot.

EXPERIMENT

The large scale gap test, described above, was used to measure the shock sensitivity of the 85% TMD propellant. This time a PMMA (Plexiglas) attenuator was used to vary the input pressure. By varying the thickness of the attenuator and critical pressure for the initiation of detonation could be determined.

RESULTS

The results are shown in Figure 4. The shock initiation pressure for stable detonation is 73 kbars. The time duration is estimated to be 1 μs from other work.

The critical energy criterion can be used to estimate the shock stimulus necessary to initiated detonation. From the above results the necessary stimulus is

$$p^2t = (73^2 x\ 1)\ \text{kbar}^2\ \mu s = 5330\ \text{kbar}^2 - \mu s.$$

The results of the previous section showed that the detonating 85% TMD porous bed generated the same pressure of 73 kbars. These results are perhaps fortuitous, but the implication is clear. At 85% TMD, the detonation is just stable. The detonation wave generates just enough stimulus to initiate the unreacted propellant ahead of it and, therefore, sustain detonation (criterion 5). These results and conclusions apply to the propellant alone; they are not dependent on charge size.

MODEL FILAMENT WOUND CASE EXPERIMENT

BACKGROUND

In the possible sequence of events, it must be shown that the porous detonating propellant can initiate detonation of the solid propellant (criterion 9). If the $p^2\tau$ criterion is invoked, then it must be shown that the stimulus generated by the detonating porous propellant is sufficient to cause the solid propellant to detonate. The stimulus generated by the detonating 85% TMD propellant is:

$$p^2\tau = (73\ \text{kbar})^2\tau = 5330\ \tau\ \text{kbar}^2\ \mu s.$$

The required stimulus to initiate merely burning in the undamaged propellant, is 6300 kbar^2 μs as determined by the aquarium test. Clearly, if τ is 1.2 μs or greater, then the porous propellant could initiate reaction of the solid propellant. In the diameter of the SRB, τ is likely to be very much greater than 1.2 μs. The conclusion is, therefore, that the porous bed will communicate deflagration and perhaps detonation to the undamaged bed (criterion 9). To test this hypothesis the following experiment was performed.

EXPERIMENT

The experiment is designed on the principle that the physics of detonation is independent of charge diameter. The only effect that conveys a size dependance is the time of arrival of lateral rarefactions that propagate from the case/air interface of the side walls of a cylindrical charge. These rarefactions limit the time duration of the detonation shock stimulus, τ. If τ is too short the $p^2\tau$ stimulus cannot initiate detonation. τ is directly proportional to charge diameter.

The experiment is shown in Figure 5. A bed of 85% TMD porous propellant is detonated by a plane wave booster assembly via a PMMA attenuator.

A plane wave booster generates a shock that is indistinguishable from that of a charge of infinite diameter. This shock is known to detonate the porous bed, based on the LSGT sensitivity results above. The resultant detonation wave was transmitted to the solid propellant under test. The length-to-diameter ratio of the solid was unity so that rarefactions could have minimal effect and thus the response was independent of charge size. Ionization gauges monitored the progress of the wave in the solid and a plexiglas (first test) or steel (subsequent test), detected the witness plate resultant effect. The PMMA was used to facilitate assembly but could not be regarded as a reliable "witness" of detonation. Improved methods of assembly allowed the steel witness to be used.

RESULTS

Four tests were fired. In the first test the propellant appeared to detonate, as evidenced by the witness plate and tube destruction, but ionization records were lost.

The ionization gauge records for the second test are shown in Figure 6. A stable wave propagation was established, and the linearity of the trace is excellent. The witness plate was punched so that there is strong evidence that the solid propellant detonated (criterion 7).

Subsequent shots were fired in which steel witness plates were used to verify the findings. The test conditions were identical to those of the previous shots. The porous propellant detonated, but did not initiated detonation of the solid. The ionization gauge records were ambiguous, so that their interpretation was meaningless; i.e., the switching times did not lie on a straight line. These records are typical of jetting between the FWC case and the propellant, a phenomenon which occurs when the shock wave velocity in the case exceeds that of the propellant. This can only occur if the propellant does not detonate. Moreover, the steel witness plates were bowed but not punched. A steel containment vessel, used to minimize damage to the NSWC firing facilities, was split into two parts by the combined effects of two tests. The vessel measured 20.5" O.D. and 15.0" I.D.; clearly, although the solid propellant did not detonate the event was highly destructive. The results are summarized in the table.

TABLE III

MODEL FILAMENT WOUND CASE, EXPERIMENTAL RESULTS

Test #	Witness	Ionization Gauge Velocity Data	Response
18	PMMA	Poor records	Deflagration or detonation witness destroyed, significant damage
19	Steel	6.73 mm/µs	Detonation, witness punched through
20	Steel	No records	Deflagration witness bowed, significant damage
21	Steel	No records	Deflagration witness bowed, significant damage

The fact that several tests failed suggests that although detonation can be induced, the stimulus produced by the detonating porous propellant is barely adequate to do so. The hypothesis that the detonating porous propellant stimulus could initiate detonation has therefore been justified; clearly a violent, disruptive event would occur in any event.

LSC ATTACK OF MODEL MOTORS

In a series of tests reported by Swisdak[8] at this meeting the effect of the LSC on model rocket motors containing TP-H1148 propellant was studied. Further tests were also performed against motors containing an inert propellant simulant, H-18.[9] Based on these tests some useful observations can be made.

The most important observation is that in none of the tests was anything more violent than a slow burning initiated. The velocity of the deflagrations typically observed in a DDT process are of the order of 0.1 km/s - 1 km/s. It can be inferred from the Swisdak tests that the burning velocities were less than 0.1 km/s to account for the effects observed. From these results it is deduced that:

(1) The LSC will induce a low order burning, Criterion (2)

(2) There is no evidence of the burning rate accelerating to deflagration velocities, Criterion (3).

These results are based on small scale tests, the question remains as to whether they are representative of larger charges, such as the SRB. They can be considered representative if the damage caused by the LSC is sufficiently localized that it does not extend to the peripheries of the model test charge. An analysis of the degrees of spallation and of jet penetration suggests that these test results are representative of what would occur in larger charges.

The results obtained when the inert propellant simulant was attacked, by the LSC, support the above conclusions. The damage in the inert material was highly localized, the material was broken into relatively large pieces and the LSC jet did not exit the slab. However great care must be exercised here. The inert material cannot fragment in exactly the same way as the live propellant for two reasons. Firstly, the material properties are not identical; secondly the combustion of the live propellant, when initiated by the LSC, must modify the resultant fragmentation.

SUMMARY OF RESULTS RELATED TO MINIMUM CRITERIA

The LSC will not promptly detonate propellant based on shock sensitivity measurements and model motor tests. The LSC will cause the shattered propellant to burn, based on model motor tests. The burning of the propellant after LSC attack does not accelerate significantly. Consequently the DDT process does not occur. The porous bed can detonate based on the shock initiation studies and the undamaged propellant can sustain detonation, at least within one charge diameter of wave propagation. The porous bed will not detonate due to the LSC shock stimulus as the energy fluence is too low. Consequently the solid undamaged propellant will not detonate. There is evidence that if the porous propellant did detonate then the solid could detonate also.It has been shown that the direct shock initiation of detonation by the LSC is impossible. There is also no evidence that burning of the damaged propellant will accelerate so that a deflagration-to-detonation DDT transition is unlikely. These two findings alone are sufficient to rule out a detonation due to deployment of the abort system.

CONCLUSIONS AND DISCUSSION

A complete detonation of the SRB is unlikely, even though it has been demonstrated that both the solid and the porous propellant can detonate. The most likely occurrence is a mild pressure burst in which the region of damage, adjacent to the LSC, will burn rapidly. The bulk of the undamaged propellant will then burn slowly.

The work reported here respresents a new approach to hazards analysis. A series of minimum criteria have been proposed that must be satisfied before a detonation is possible. The data obtained were not dependent on the size of the propellant samples. Consequently this approach is applicable to energetic materials of any critical diameter, only laboratory scale tests need be performed. Clearly much work must be done to refine the test methods used and to obtain a method for quantifying the statistical probability of a violent event and its magnitude.

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AN INVESTIGATION OF THE SYMPATHETIC EXPLOSION OF LOOSE LOADED TNT IN LARGE QUANTITY

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The sympathetic explosion phenomena of explosives, especially of loose loaded explosives, are very complicated. The most investigations of sympathetic explosions in the past were made with a smaller quantity at a higher density.

We have determined the sympathetic explosion times and the shock velocities in the acceptors. By the sympathetic explosion time, we mean the time interval from the time the shock wave from the detonation of the donor charge reaches the surface of the acceptor to the time the acceptor explodes. For the purpose of measurement, we have developed a kind of grate type probes. They can send a signal at the moment of explosion of the acceptor charge.

Two groups of tests were conducted. One was in small quantities. The explosive quantities in donor and acceptor charges were the same, both in 0.3 or 0.5 kg. The other was in large quantities. The donor charges were 0.5 or 4 tons, and the acceptor charges were 47 kg in every trial. All of the charges were made in the shape of a cylinder. The ratio of diameter to length is 1:1. The grain size of loose loaded TNT we used was not controlled and screened. The bulk density of charges is about 0.88 g/cm^3. All of the tests were conducted at a flat field. The donor was placed vertically and 4 acceptors were arranged surrounding the donor at different distances with one end opposite the donor. A grate type probe was set along the axis of every acceptor in order to give a signal as soon as the acceptor explodes, and another probe made of cupper foiles was set at the surface of the acceptor in order to give a signal at the moment of the arrival of the shock wave from the donor. These signals via a signal converter were recorded by some oscillographs or a multichannel chronometer. On the other hand, in some tests, several copper foil probes were set in one of the acceptors at different distances from the surface in order to determine the shock wave velocity in the acceptor.

The sympathetic explosion times ts that we have determined are in the order of several tens μS to several hundreds μS. They are much longer than predicted. We have found that the sympathetic explosion time quickly increases with the increase of the distance R of acceptor from the center of explosion. It is assumed that when the distance of acceptor from the center of explosion is equal to the radius of donor Ro, then ts=0. The equation used for fitting the data obtained is

$$R - Ro = a \exp(-\frac{b}{ts})$$

where a and b are two empirical constants, which are different with different weights of donors. It is also assumed that the value of a + Ro is the critical distance R^* of sympathetic explosion at that weight of donor W. So we can make a rough estimate of critical distance of sympathetic explosion with only a few tests, even with one test. This is convenient for explosion tests with large quantities of explosives. The results obtained agree with those obtained by other methods and are shown in fig. 1 and table 1. In table 1, the critical scaled distances $K = R^*W^{-\frac{1}{3}}$ with different weight of donor W are also listed. It can be seen that the critical scaled distance of sympathetic explosion with large quantity of donor is larger than that with small quantity of donor. For engineering use, we propose the following formula as a rough estimate of the critical distance R^* with a large quantity of TNT

$$R^* = 0.7\ W^{\frac{1}{3}}$$

The results of the measurements of the shock wave velocity in acceptor charges are shown in table 2. It is found that the shock wave transmitted in acceptor will change into deflagration of about 4mm/μs at the middle of the acceptor charge if its velocity is about 0.8 to 0.9mm/μs. But while its velocity is about 0.5mm/μs or less, the shock wave will decline gradually. By the visual examination at the site after tests, it is confirmed that in the former case, the acceptors are really exploded but in the latter case are not.

The following equation can be used as the Hugoniot of loose loaded TNT (1,2):

$$D = 0.3 + 1.7\,u$$

where D is the shock velocity (mm/μs) transmitted into acceptor , and u is the partical velocity (mm/μs). The shock pressure P transmitted into acceptor can be estimated by the relationship at the shock front:

$$P = \rho_0 D u$$

According to the results obtained, we may estimate that the critical pressure of sympathetic explosions of loose loaded TNT at the bulk density about 0.88g/cm^3 is about 1 to 2 kbars. Generally, in the shock wave initiation experiments at high density and small quantity of charge, the critical initiation pressure of TNT is above several kbars. It is reported by Cook that critical pressure of shock initiation of TNT in small quantity at density of 0.85 is about 4.5 kbars (3) . But the critical pressure of shock initiation of large quantity loose loaded TNT must be some lower, as mentioned above.

The confidence interval of any sympathetic explosion experiment data is very broad and the explosion experiment with large quantity of explosives can not be repeated a lot. Therefore, the related critical values can only be estimated very roughly with a few tests.

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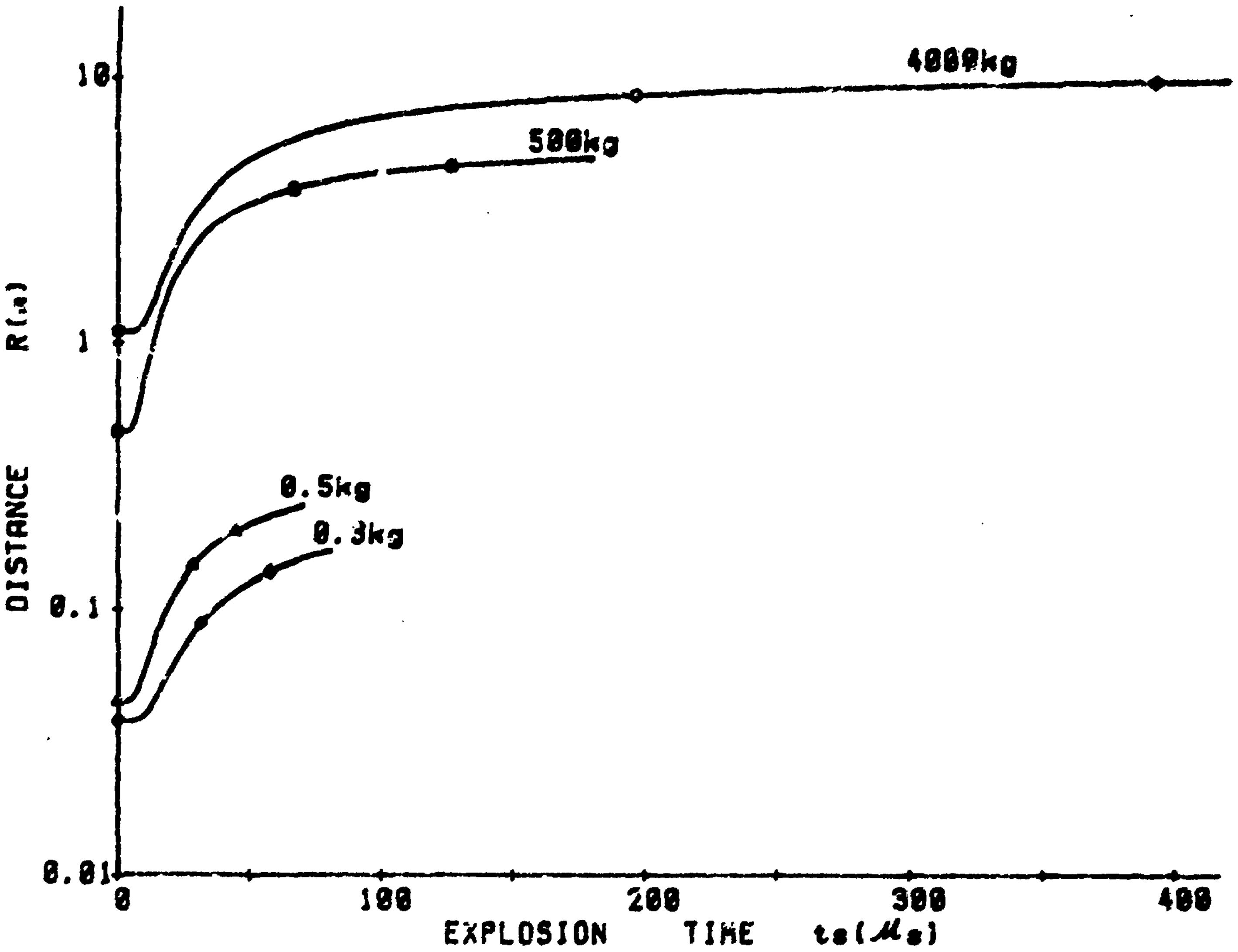

Fig. 1. The Relationship Between Distance and Explosion Time with Different Donor Weight

Table 1. Critical Distance of Sympathetic explosion

Donor Weight W (kg)	Critical Distance R^* (m)	$K = R^* W^{-\frac{1}{3}}$
0.3	0.27	0.4
0.5	0.36	0.45
500	5.7	0.72
4000	10.4	0.66

Table 2. Shock Velocity in Acceptor Charges

Donor Weight	Distance between Acceptor and Explosion Center		The First Half of the Charge		The Latter Half of the Charge	
0.5 kg	0.145 m	Distance between Probes mm	50		50	
		Timeμs	56.5		32.0	
		Velocity mm/μs	0.885		1.56	
		Pressure kb	2.7			
500 kg	5 m	Distance between Probes mm	175	175	175	175
		Timeμs	185	244	/	40
		Velocity mm/μs	0.945	0.717	/	4.38
		Mean Velocity	0.832			
		Pressure kb	2.3			
4 T	11 m	Distance between Probes mm	175	175	175	175
		Timeμs	406	344	/	472
		Velocity mm/μs	0.431	0.509	/	0.371
		Mean Velocity	0.47			
		Pressure kb	0.41			

Technical Investigation of 11 January 1985
PERSHING II Motor Fire

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ABSTRACT

This paper describes the result of an accident investigation performed by a technical team at the US Army Missile Command, Redstone Arsenal, Alabama in support of the US Army Safety Command, Ft. Rucker, Alabama. The accident occurred near Heilbronn, Federal Republic of Germany, on January 11, 1985. A PERSHING II first stage motor burned as a result of efforts to remove it from its shipping container and place it on an erector launcher (EL).

Several possible causes of the motor ignition were considered during the course of the investigation. These were: crew error, incorrect procedures, sabotage, failure of mechanical parts, electrical short circuits, propellant defects, failure of other components mounted in the motor, and electromagnetic effects (radio frequency radiation, lightning, and electrostatic discharge (ESD)). After an intense three month investigation involving many government and private laboratories and researchers. All of these possible causes except ESD were eliminated from further investigation efforts because they were an unlikely, highly unlikely or impossible cause of the accident. Elimination of a cause was based on the results of witness statements (60), reasonable experimental data, debris examinations, computer analyses, and analytical calculations.

ESD was determined to be the only plausible explanation for the accidental motor burning. Tests devised and conducted by the Electro-Magnetic Effects (EME) Team to discover the source of electrostatic charges, the migration of the charges to a critical location, and the effects of the charges on the propellant system have confirmed the postulated scenario. A series of tests designed to demonstrate and verify this conclusion has been conducted, resulting in a more detailed understanding of the exact sequence which resulted in the propellant ignition.

When the motor was lifted from the silicone foam rubber cradle pads, it was charged to a high, positive potential (with respect to the steel cradle) in the region between 130° to 160° from top dead center. The cradle pad was charge negatively in that region. Lifting the motor away from the cradle enhanced the energy and resulted in a redistribution of the electric field also into the propellant. Because the boom extension put lateral force on the motor, once it was free from the front thrust groove, the motor moved up and aft suddenly contacting the end cross beam at the end of the container with the skirt and nozzle and also at the top of the cradle edge with the side of the motor. This caused an arc discharge of the dielectric motor surface, thereby generating very high transient electric fields within the propellant chamber. This resulted in electric field stress breakdown of the hydroxyterminated polybutadiene (HTPB) binder within the propellant, activation of the oxidizer, and ignition of the propellant as the oxidizer reacted with the fuel of the propellant. The stiffness of the propellant grain and the case restricted gas expansion and created a high temperature region which supported further burning and pressure increase. After a

relatively short period (approximately one second) the mechanical stress on the grain from the high pressure pocket caused a sudden collapse of the grain. But, the rapid decrease in pressure due to the sudden increase in volume was insufficient to extinguish the fire. Collapse of the grain was such that it blocked gas flow through the nozzle, resulting in increased pressure buildup and ignition of an increasing surface of propellant. Soon the pressure was above the limits of the strength of the case and the aft end of the propulsion section was blown off. This violent rupture dismembered the lifting fixture and threw lethal debris about the accident site. A large mass of propellant was then expelled through the aft hole in the opened cylinder and the reactive forces drove the remaining forward section, propellant, and container into the Maschinenfabrik Ausburg-Nuremburg (M.A.N.) crane/tractor vehicle. Flying debris and flame were responsible for fatalities and injuries suffered by personnel assembled around the missile assembly site.

General Description of the PII First Stage Rocket Motor

A PII missile is assembled from five major sections. The first stage rocket motor is the largest and heaviest of the five sections. The first stage rocket motor is 144.74 inches (3.63 meters) long, 40 inches in diameter (1.02m) and weighs 9,145 pounds (4,148 kg). Most of the weight is the solid fuel rocket propellant. The rocket motor case is made of Kevlar filament and epoxy resin. Two cylindrical aluminum sections attached to the forward and aft ends of the rocket motor case provide four hard points used in lifting the section.

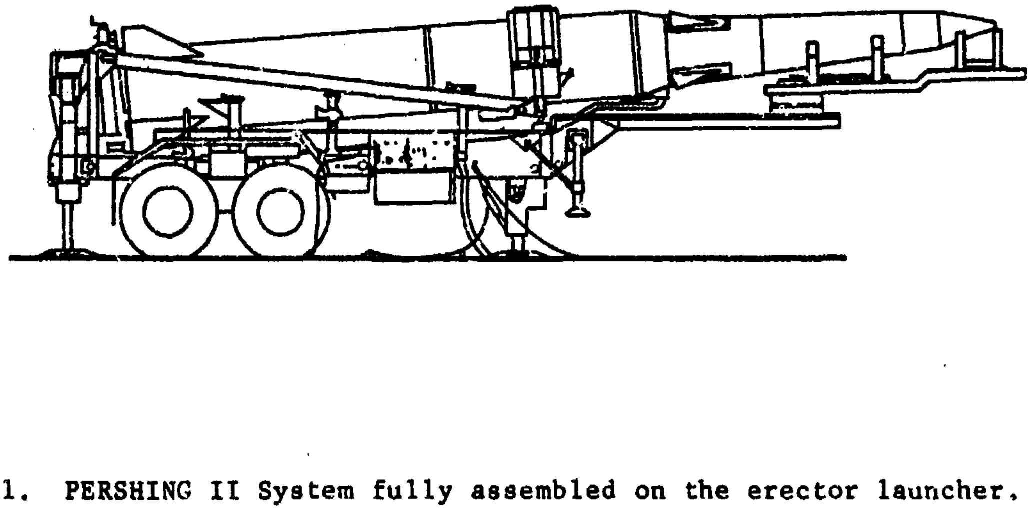


Figure 1. PERSHING II System fully assembled on the erector launcher.

Sequence of Events for the Accident Motor

The motor was manufactured during the summer of 1984 at Hercules, Inc. Magna, UT, accepted by the US Government on October 29, 1984, and shipped to Pueblo Army Depot Activity, Pueblo, CO, the same day. The aft skirt and other items required to complete assembly were installed at Pueblo, and the complete rocket motor, serial number P/S 12037, was placed in a steel shipping and storage container. It was then shipped to Germany in early December 1984, arriving at the "Ft. Redleg" complex on December 19. It was stored outside in its shipping container in a holding area until January 9, 1985, during a period of severe cold weather, with recorded night time temperatures below 0^o (-17.8^oC).

On January 9, 1985, rocket motor P/S 12037 was moved in its container from the holding area to a training assembly area on the Ft. Redleg complex.

In a typical assembly operation, rocket motors in their containers are placed side-by-side on the ground in close proximity to the erector launcher (EL). Next, the upper halves of the containers are removed, hoisting beams are attached to the sections and the sections are lifted out of their containers in sequence and lowered in place on the EL for mating to complete the assembly. Lifting is accomplished with a 10-ton hydraulic crane mounted on the M.A.N. tractor, which also serves as the prime mover for the EL. The M.A.N. tractor is positioned between the rocket motors and the EL during the operation.

Shortly before 2 p.m. on January 11, 1985, soldiers from a firing platoon of "C" Battery, 3rd Battalion, 84th Field Artillery, prepared to lift the rocket motor from its container to begin a missile assembly as part of their rountine training. There were 10 soldiers in proximity to the rocket motor, including a Captain who supervised the operation. Other soldiers were standing on the EL ready to receive the rocket motor for assembly. Assigned work was going on elsewhere in the immediate area by soliders not involved in the assembly operation.

The container holding rocket motor P/S 12037 had been placed perpendicular to the center line of the M.A.N. tractor with the aft end (nozzle end) of the motor pointing away from the tractor. As a normal procedure, another open container holding a second stage motor was beside the container holding rocket motor P/S 12037. Hoisting beams had been attached to both motors. All mechanical and electrical support equipment needed for the operation were turned on and were operating properly. The engine of the M.A.N. tractor was running to provide power to the crane. A 30 kW generator mounted on the tractor (used to provide power to the EL) was operating. Its circuit breaker was properly set in the "Off" position and the generator was functioning correctly.

The soldiers followed established procedures. Grounding connections were in place. No nuclear materials were in the area since they are never carried or present during training and field exercises.

Although it was not snowing, the ground was covered with snow and the sky was overcast. The air temperature was about 20^oF (-7^oC), but the motor temperature was about 10^oF (-12.2^oC).

At about 1:53 p.m., an attempt was made to lift rocket motor P/S 12037 from its container. A groove in the forward attachment ring of the rocket motor fits over a metal flange within the shipping container to prevent fore and aft movement of the rocket while being transported in the container.

Unless the rocket motor is level as it is being lifted, binding can occur between the container flange and the groove in the forward attachment ring. This happened in the first lift attempt. Although the aft end (nozzle end) of the rocket motor lifted about 5 inches (0.13 m), the forward end hung up, preventing the rocket motor from being lifted clear of the container. The lift was halted and the aft end of the rocket motor was lowered back into the container.

The crane boom position was repositioned (extended) and a second lift began. The rocket motor hung up momentarily, then released, causing the forward end to rise about 7 inches (0.178 m). The motor moved toward the starboard rear a few inches and the aft end bumped a steel cross member in the container as the side bumped the cradle. It was at this time, based on witness statements, that the motor caught fire and burned.

Due to the abnormal burning, pressure in the motor case increased beyond the strength of the case. The case ruptured in less than one second.

The aft dome of the motor (a hemispherical section of Kevlar), the nozzle attached to it with bolts, and the entire aft skirt to which it is attached, were expelled rearward together with numerous burning pieces of propellant. The aft dome, nozzle and aft skirt were later recovered about 410 feet (125 m) from the site of the fire.

When the motor case ruptured, it caused the hoist beam to fail, dropping the remaining forward portion of the motor into the container, where it continued to burn. At the same time, the container was driven forward approximately three feet (1 m) until it contacted the rear wheels of the M.A.N. tractor.

A consequence of debris analyses, this sequence of events first suggested the conclusion of the investigation that ignition was abnormal and occurred near the outside surface of the propellant grain (the portion nearest to the inside wall of the motor case) at a point about 94 inches (2.4 m) aft of the forward end of the rocket motor, at a location in proximity to the rear support cradle in the container. In a normal ignition sequence, the igniter in the forward end of the rocket motor flashes fire down a lengthwise cylindrical cavity through the center of the motor. The propellant then burns from the center outward toward the case wall. The proof that this was not a normal ignition is that the igniter was recovered in an unfired condition. The igniter had not been actuated.

Three soldiers, all in proximity to the motor when it caught fire, were killed. Nine others also in proximity were hospitalized. The heavy winter clothing (gloves, boots, parkas with hoods, etc.) worn by the soldiers, because of the cold weather, reduced the number and severity of burn injuries.

The second stage motor placed beside the first stage motor P/S 12037 was exposed to the fire and sustained scorching and heat damage but did not burn. The M.A.N. tractor was damaged. The EL was slightly damaged by impact from the M.A.N. tractor which tilted into its sides.

Methodology of the Accident Investigation

Elimination of Possible Cause

To determine the cause of this accident, all possible causes were investigated, by using available records, witness statements, analysis of recovered debris, and additional tests and calculations. The investigative technique used to accomplish this was by a fault tree analysis. The purpose of a fault tree analysis is to determine the logical interrelation of possible causes (faults) that might have resulted in the undesired event. The goal of this analysis was to determine the parameters governing an undesired ignition of the propellant and to list the possible causes in the order of the probability of their occurrence. This approach quickly narrowed the scope of the investigation. The scope and depth of this effort was reflected in the cost-approximately six million dollars.

Propulsion experts with considerable experience in this field assembled a list of all possible causes for the propulsion section malfunction. Using this list, they systematically constructed a fault tree for use during the accident investigation. Supporting the fault tree resulted in documents covering hundreds of tests and analyses. Through these tests, analyses, and calculations certain possible causes were eliminated as unreasonable. Chemical incompatability, abnormal motor manufacture and sabotage were scrutinized but rejected as possible causes. Other areas found as not having a sufficient rate of energy density in this accident sequence were (1) heat, (2) friction, (3) impact, and (4) electrical or electromagnetic sources -- other than ESD. Therefore, only mechanical and electrostatic effects remained to be investigated. Simulated mechanical and thermal loads, as may occur in the course of transport, storage, and handling, were further analyzed, including some additional tests. Further testing and analyses confirmed that the mechanical loads by themselves did not affect either the safety or the functioning of the first stage rocket motor. Under the given circumstances, purely mechanical causes were considered to be improbable and eliminated from further discussion. Hence, ESD was intensively investigated.

The Root Cause of the Accident

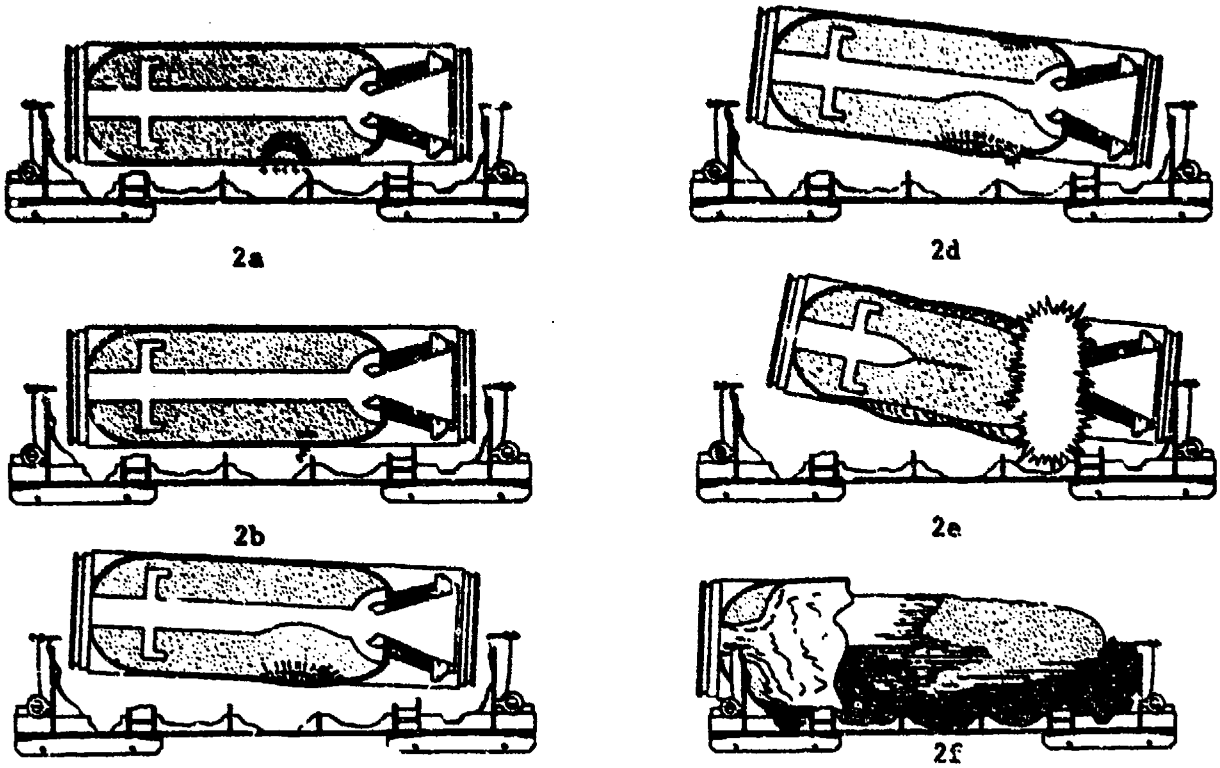
The outcome of this investigative process resulted in pragmatically eliminating all known possible causes -- except ESD, i.e., a discharge of electrostatic electricity, possibly in connection with mechanical effects in the propellant grain. Proof of this outcome was obtained from subscale and fullscale experiments, mathematical modeling, and analysis of the debris. The following sequence of events emerged from this process.

Technical Sequence of Events in the Motor

The sequence of events was determined from debris analysis and laboratory experiments, then further refined by observations made during demonstration tests. This sequence is depicted by the series of drawings shown in figure 2.

As the rocket motor was being lifted from the container, the separation of the Kevlar rocket motor case from the silicone rubber pads resulted in the creation of a static electric charge by a triboelectric process (see figure 1a). The charge was localized on the motor surface in the area above the pads and on the pads. In tests on tactical, full scale motors being separated from a shipping container cradle it has been found that the high charge density areas (hot spots) tended to be localized to the region between 130° and 160° from the top of the motor. Further, due to the fit of a specific motor into a specific container, these hot spots tended to be repeatedly created in certain areas. The density of the electrostatic charge has been shown to increase as the temperature and humidity decreased. The charge created by triboelectrification of the polyurethane painted Kevlar case does not dissipate rapidly. This is especially true in conditions of low temperature and low humidity. This charge gave rise to considerable electrial fields between the motor surface and also in the propellant grain. The motor moved up and back, bumping the steel cradle, and resulted in an external ESD. As a result, a subsurface electric arc occurred in the aft lower portion of the propellant resulting in propellant ignition as indicated by figures 2b and 2c. Such an internal arc can take place without puncturing the motor case. Furthermore, it was demonstrated by independent tests that the electrical field strength and the total electrostatic energy accumulated in the whole system are sufficient for electrical breakdown and/or ignition of the propellant.

The epicenter of the event was located between 130° and 150° of rotation, and approximately 94 inches aft of the forward surface of the propellant grain. The flame stabilized in a gas pocket between the bond-line and the grain, and the aft section of the grain started to implode. See figure 2c. The flame spread forward and aft at a higher rate than the circumferential rate. The stiffness of the propellant grain and the case restricted gas expansion and created a high temperature region which supported further burning and pressure increase. The mechanical stress on the grain from the high pressure packet caused a sudden, partial collapse of the center bore of the grain in the region of the gas pocket. But, the rapid decrease in pressure due to the sudden increase in volume was insufficient to extinguish the fire. Collapse of the grain center bore progressed fore and aft, reaching the aft end first, such that it blocked gas flow through the nozzle. This resulted in an increased pressure buildup and ignition of an increasing surface of propellant. Soon the pressure was above the limits of the strength of the case (see figures 2d and 2e) and the aft end of the propulsion section was expelled aft. At nearly the same time, the expanding gas pocket had reached and broken into the forward cavity. Again, the decrease in pressure was insufficient to extinguish the fire. The pressure built rapidly within the forward cavity since the bore was completely collapsed causing about 4000 pounds (1800 kg) of propellant to be expelled approximately 50 meters aft of the incident site where it burned. See figure 2f. The reactive force simultaneously moved the head end of the motor and container forward, approximately one meter, to rest against the truck used in the assembly.



2a 2d

2b 2e

2c 2f

Figure 2a-f. Sequence of events as PII first stage motor was being removed from its shipping container which led to the motor fire and damage. Figure 2a shows a positively charged patch on the outer surface of the composite PII motor case created by the silicone foam rubber cradle pads of the container. An external arc discharge resulting in the internal arc is shown in 2b. Figures 2c and 2d show the progressive expansion of the localized high pressure area causing case failure which resulted in the collapse of the grain, shown in 2e, and the separation of the nozzle/aft skirt section. Figure 2f shows the result of the high pressure pocket formed in the "P-groove" area in the front of the propellant grain.

Propellant Safety Assurance Prior to Accident and New Findings

The Pershing II first stage rocket motor contains a customary ammonium perchlorate HTPB propellant which - compared with other similar propellants - is less sensitive to external stimuli. It will not detonate, but can and does burn very rapidly. This burning can cause rapid over-pressurization of the motor case if abnormal burning occurs or the exit port (nozzle) becomes blocked. This over-pressurization results in the bursting of the motor case -- as occurred in this accident.

Prior to the Pershing II accident, extensive testing was done to ensure system safety. Among these tests were those dealing with propellant sensitivity. The propellant was characterized by the existing state-of-the-art tests and determined to be insensitive to levels higher than those in any expected adverse environment, including ESD. During the course of the accident investigation, phenomena were discovered which have required the propulsion community to reassess and redesign testing techniques for propellant. It has been found that: (1) an internal electrical breakdown of the propellant, due to a transient electromagnetic field, can result in ignition of this propellant; and (2) it has been shown that propellant temperature and sample volume are critical to proper evaluation of its response to ESD.

Knowledge of the presence of these phenomena has allowed corrective actions to be taken on the present system and eliminate future accidents of this nature on this and other designs.

Replication and Verifications Tests

To confirm that the propellant was most probably ignited by ESD phenomena required evaluation based on measurements of:

(1) charges and electrical fields generated during the lift,
(2) where the charges migrate and at what rate, and
(3) the response (sensitivity) of the propellant to ESD phenomena.

Replication tests were conducted to further investigate the ESD ignition scenarios. These tests involved actual and simulated removal of a live tactical propulsion section from its container. This motor was as nearly identical in construction and history to the incident motor as possible. The tests were conducted at temperatures as near as possible to those involved in the accident. The relative humidity was also controlled to avoid frost accumulation, which did not exist at the accident site. When the motor was lifted from the container in the manner which resulted in the 11 January 1985 accident, generation of very high electrostatic charge densities was confirmed. As predicted prior to the test, the motor did not ignite due to the low probability of exactly duplicating all of the necessary events of the accident. Following the duplication phase of the test sequence, multiple lifts were conducted to determine the possible build-up of charge due to multiple contacts. In this phase, it was repeatedly shown that the charge density did not significantly increase with additional lifts. Finally, simulated lifts were conducted. This phase of testing provided more control of the charging, charge distribution, and discharging of the motor/cradle pad interface area. These tests were also conducted at low temperatures and relative humidities. When the motor pad was charged to a 50 kV potential with respect to the container structure and then discharged via an arc discharge, the propellant was ignited in the subsurface region of the grain. This demonstrated the "sympathetic" ignition scenario wherein an external ESD arc creates an electrical arc in the propellant near the case bond interface without penetrating the case.

Conclusion

In reviewing the total data base generated in the investigation, the critical events leading to the accidental propellant ignition were:

(1) Triboelectrification of the insulating motor case.

(2) Location of the charge distribution of the motor.

(3) Contact between the motor and the aft steel cradle at that location.

(4) An external ESD from the motor case to the container at the contact point creating very high E-field stresses within the propellant.

(5) Sufficiently cold temperatures of the system such that:
  a. charge generation of the motor case was enhanced,
  b. charge retention was enhaced.
  c. susceptibility thresholds of the propellant to both E-field and energy was significantly reduced.

Hence, a duplication of the accident would require more than similar conditions of temperature, humidity, and movement. It would also require exact timing, motor positioning in the cradle to produce charging at a precise location, and finally specific movements of the motor to bring the charged area within discharging distance of the steel container. Tests have confirmed that if this scenario occurred, the propellant grains could be ignited with an unmodified system. That all of these necessary conditions would coincide at one time was, indeed, a very remote possibility.

Acknowledgements - The authors would like to acknowledge the efforts of the many individuals which significantly contributed to the successful conclusion of this accident investigation. Because the list of names is long, only their organizations will be listed. We gratefully thank the U.S. Army Missile Command (MICOM) Technical Team, MICOM Technical Review Team, Independent Review Team, Electromagnetic Applications, Inc. (EMA), Lightning and Transient Research Institute (LTRI), Martin Marietta Aerospace/Orlando (MMAO), Hercules, Inc. (HI), Technology Research Assoc., Inc. (TRA), U.S. Army Ballistic Missile Defense System Command, Auburn University Physics Department, Societe Nationale Des Poudres at Explosifs (SNPE), and the University of Alabama (Huntsville).

DEBRIS HAZARD AT A ROCKET MOTOR TEST CELL FACILITY-- AN "ACCIDENTAL" STUDY

by

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ABSTRACT

The J-5 test cell at Arnold Engineering Development Center (AEDC) is the only national facility for testing large solid-propellant rocket motors at simulated flight-altitude conditions. However, the cell was not sited to meet the quantity-distance criteria required for testing motors containing propellant equivalent to 20,000 lb of TNT. This motor and other motors containing similar propellant amounts were being tested in J-5 using explosives safety waivers since no other facility is available in which to test them. Safety personnel concerned with the serious potential hazards for other unique test capabilities at AEDC funded a study to examine the distribution of debris and define the hazard at the J-5 test cell resulting from accidental detonation of rocket motors containing propellant equivalent to 20,000 and 30,000 lb of TNT. While the study was in progress, an actual mishap occurred during a test of one of the motors being examined in the study. The estimated sequence of events during the mishap and the distribution of motor, test cell, and building debris after the accident as compared with predicted debris arcs are presented in this paper.

1.0 INTRODUCTION

Southwest Research Institute (SwRI), as a subcontractor to Lawrence Livermore National Laboratory (LLNL), has been consulting Arnold Engineering Development Center (AEDC) on potential debris distribution problems at the J-5 and proposed J-6 rocket test facilities. The J-5 test facility at AEDC, shown in Figure 1, is the only large national facility for testing solid propellant rocket motors at simulated flight-altitude conditions. However, some motors currently in need of altitude testing and future motors to be tested exceed the test capability of J-5 in nominal thrust and in the amount of propellant contained in the motors. Some of these motors were being tested in J-5 with explosives safety waivers since the location of the facility does not meet quantity-distance criteria required by safety regulations for the type and amount of propellant involved. Safety personnel became concerned with the potential debris hazard which may result from testing motors under safety waivers.

In November 1985, SwRI was analyzing the distribution of debris which would result from an accidental detonation of propellant equivalent to 20,000 and 30,000 lb of TNT in the J-5 test cell. On November 23, 1985, during a qualification test of a rocket motor, a mishap occurred. At the request of LLNL and with permission from AEDC, an SwRI team was sent to investigate the mishap site with special emphasis on collecting data on the distribution, size and nature of the resultant debris created by the event. This paper summarizes SwRI's investigation and post-mishap analysis results. Debris hazard zones predicted for an accident at J-5 are compared to the actual distribution of motor, test cell, and building debris after the mishap.

2.0 ANALYTICAL DEBRIS DISTRIBUTION STUDY

The emphasis of the original analytical study of the rocket motor detonation was the distribution of debris from the J-5 enclosure building, the test cell and the motor being tested. A previous study (Reference 1) conducted by SwRI to analytically determine the debris distribution around an accidental motor detonation indicated directional debris throw and the existence of some

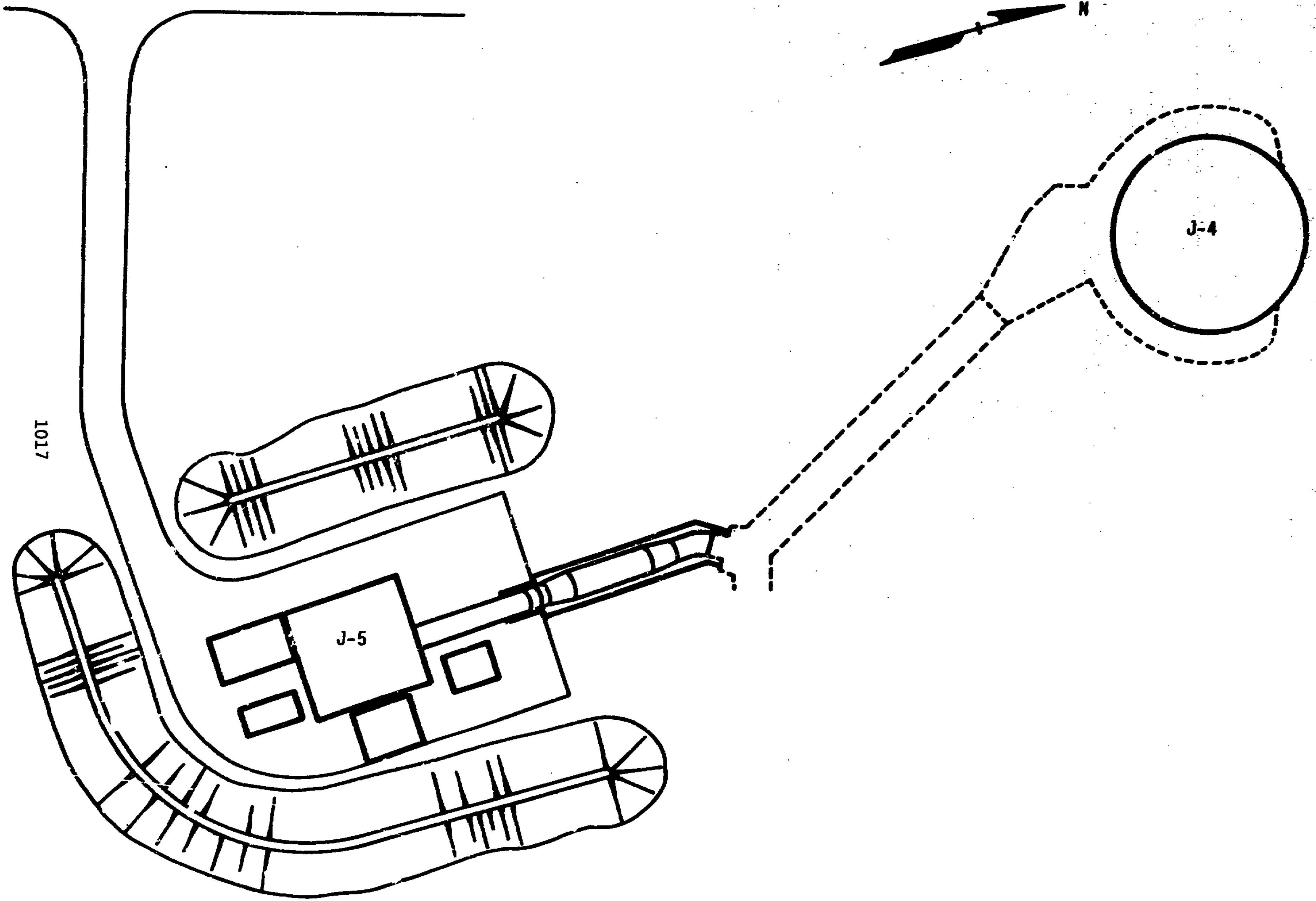
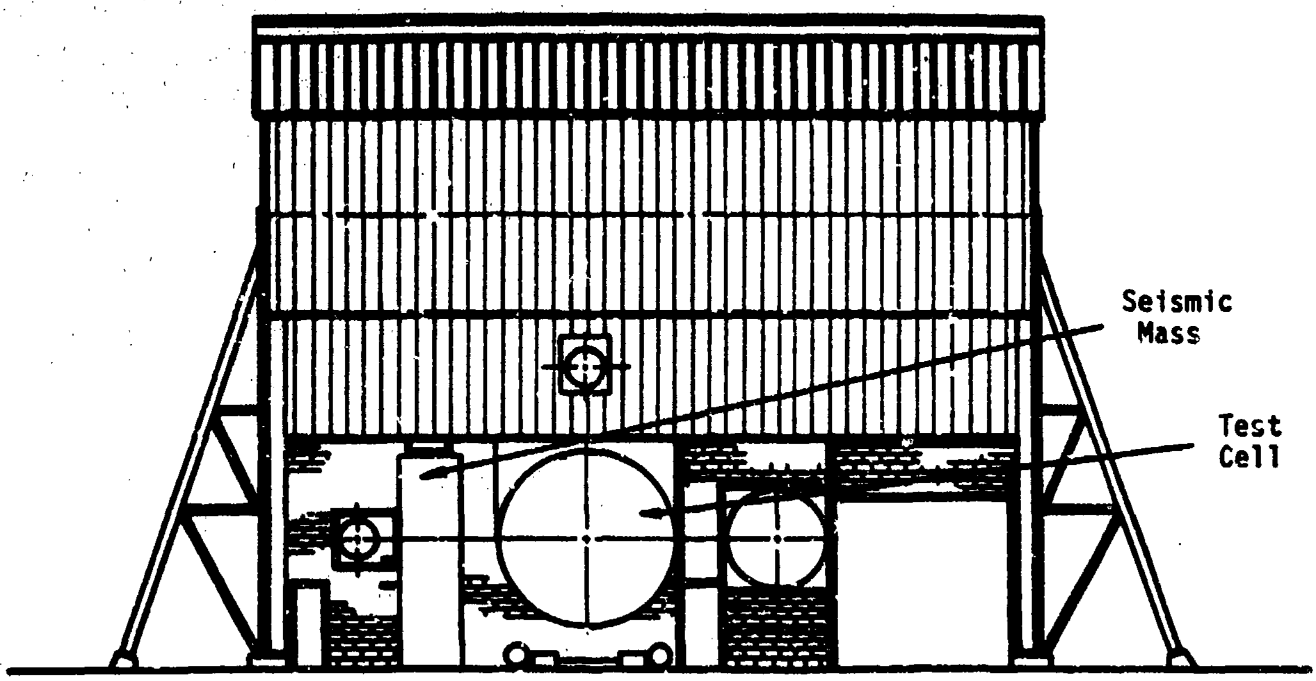


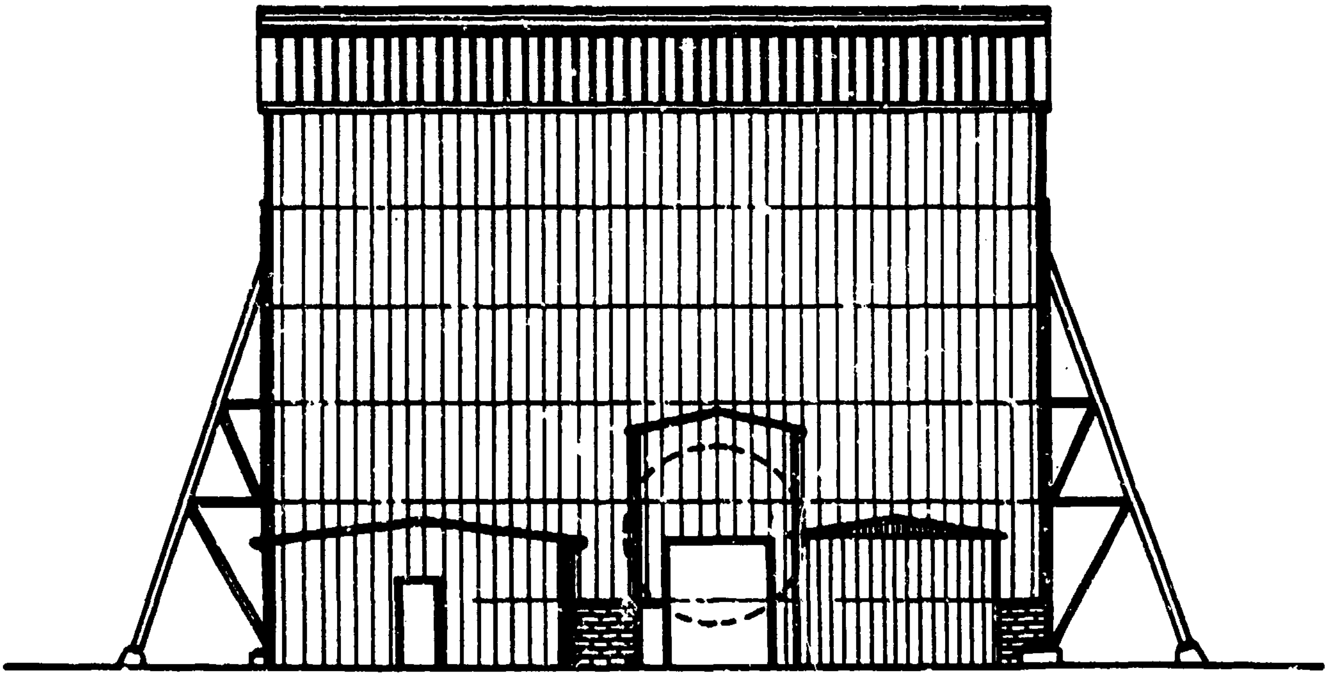
Figure 1. AEDC J-5 Test Facility

relatively debris-free zones around the site. That study was for a proposed large altitude rocket motor test facility (J-6 facility) at AEDC which consists mainly of a large steel test cell and a steel frame, metal siding enclosure building. Hazardous debris densities were determined within various zones around the test cell. The zone boundaries were based on the shape and position of the test cell and on experimental work examining debris distribution from explosions in aircraft shelters (References 2 and 3) and in buildings (Reference 4). The horizontal position of the cylindrical cell made it reasonable to assume cell and motor fragments would be dispersed perpendicular to the axial length of the cell with a limited number of fragments thrown in directions normal to the endcaps. The distribution of building fragments would be concentrated directly out from the walls, with relatively debris-free zones in directions about 45 degrees from the normals to the walls. Although the supporting data were all for reinforced concrete structures, a similar distribution was expected for an explosion inside a predominantly corrugated metal structure.

Elevations of the J-5 enclosure building and an expanded detail of the test cell are shown in Figures 2-4. Since the J-5 test cell and enclosure building are similar to the configuration described in Reference 1, debris were expected to be similarly distributed in zones around the enclosure building. The zones which were established for examining hazardous debris densities are shown in Figure 5. Debris densities were estimated in zones 1, 3, 5 and 7 since the number of debris landing in the other zones was assumed to be minimal. Building debris will be dispersed in directions normal to the walls of the enclosure building. The heaviest concentration of motor casing and test cell fragments was predicted in zone 5 because it extends perpendicular to the horizontal axis of the test cell. Approximately 70% of the total fragments and debris will land in zone 5. Although zone 1 extends in the direction opposite of zone 5, fewer casing and cell fragments will land there since a 5 foot thick seismic mass (see Figure 2) supports the test cell on that side. The seismic mass will stop all but high trajectory fragments. About 20% of the total debris will land in zone 1. The remaining 10% of the debris will be distributed in zones 3 and 7, with slightly more debris landing

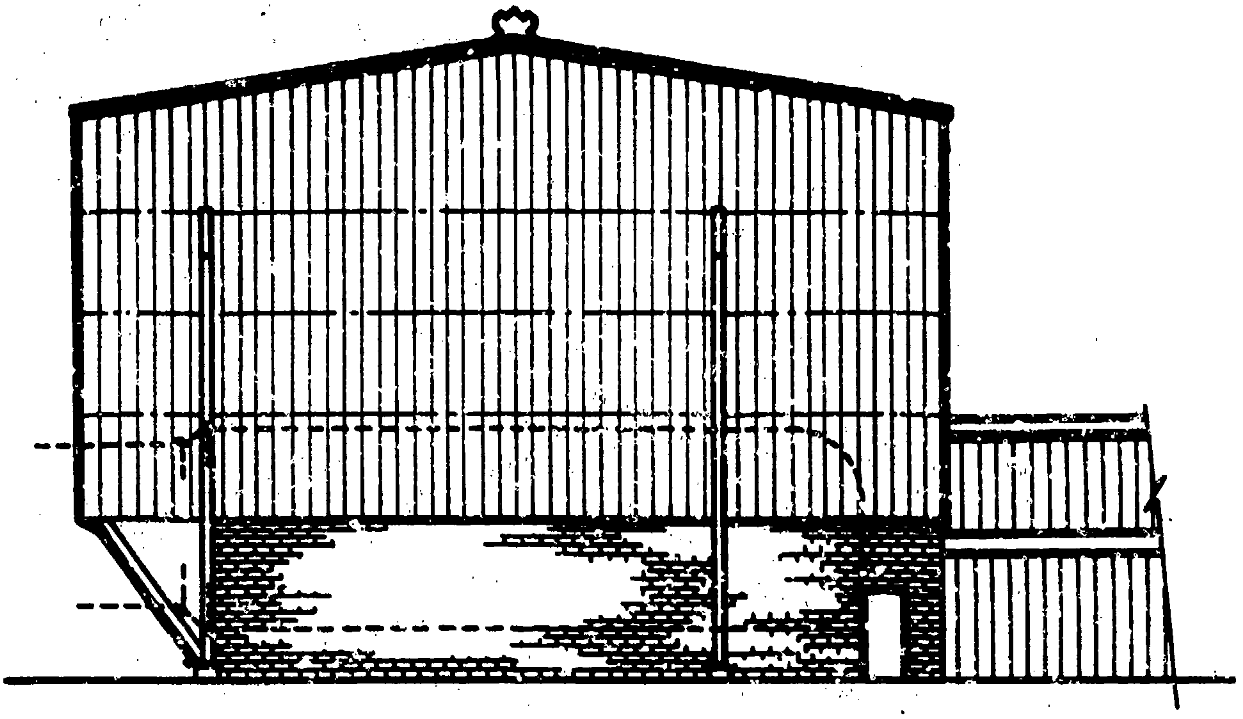


a) North Elevation

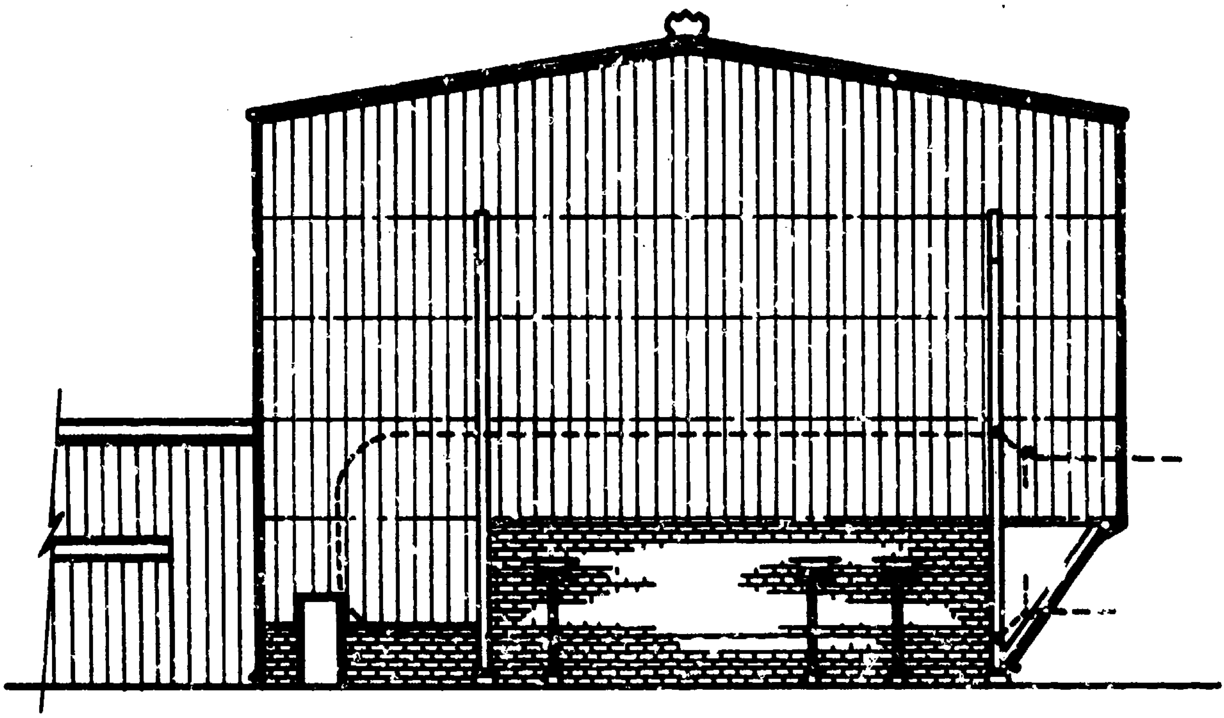


b) South Elevation

Figure 2. J-5 Facility Elevations



a) West Elevation



b) East Elevation

Figure 3. J-5 Facility Elevations

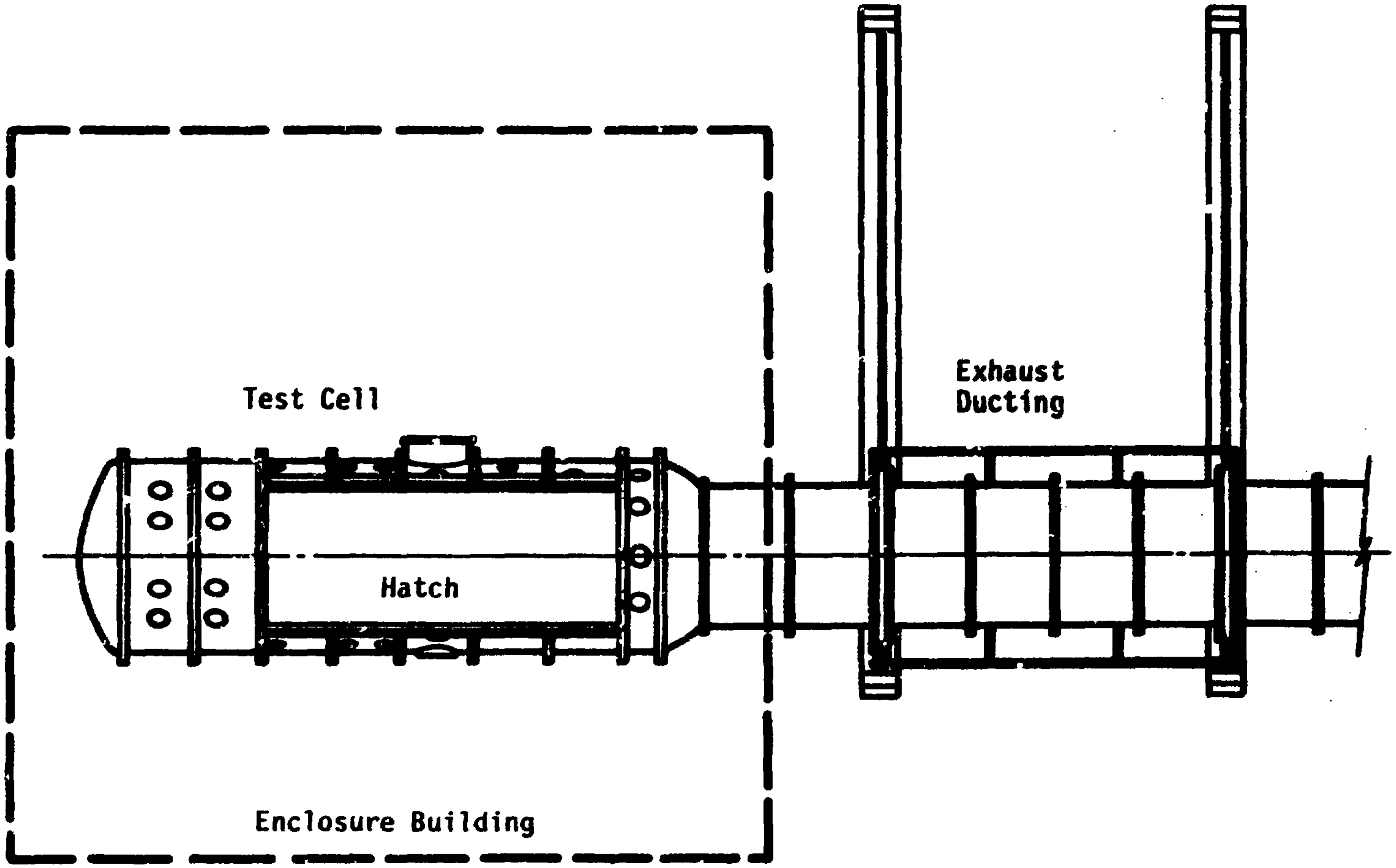


Figure 4. Detail of J-5 Test Cell

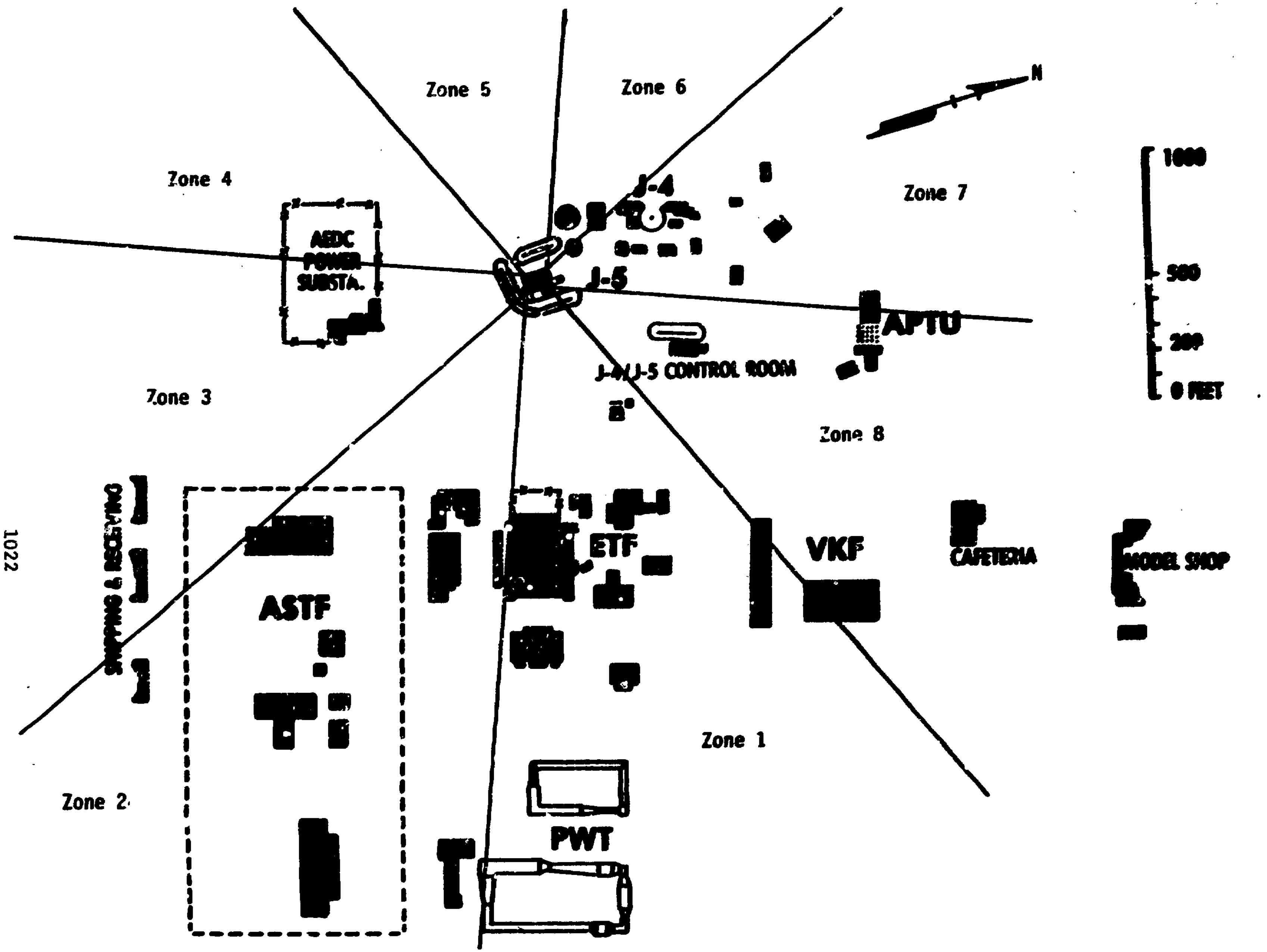


Figure 5. Debris Zones for an Explosion in J-5

in zone 3. The percentage of debris landing in zones 2, 4, 6 and 8 is insignificant. It should be noted that while the percentage of fragments landing in zones 3 and 7 is relatively low, the cell endcaps and hatch covers will most likely impact in these areas. Thus, the damage potential of these large debris is a more important consideration than hazardous debris density in the immediate J-5 area. In summary, the distribution of fragments and building debris was expected to be highly directional with heavy debris concentrations in zones normal to the walls of the enclosure building. Debris paths and concentrations of major debris observed during the mishap investigation lend new support to this theory.

3.0 MISHAP SITE INVESTIGATION

The test being conducted prior to the mishap involved a qualification test of a large rocket motor containing Class/Div. 1.1 propellant. The pressure inside the motor measured about 600 psi just before failure occurred. The peak pressure of 740 psi was measured about 10 seconds into the test. It was estimated that approximately 1100 lb of the original 16,000 lb of propellant remained in the motor when the failure occurred.

An AEDC mishap investigation team was immediately set to the task of determining the cause of the mishap. Their activities included review of manufacturing, shipping and test preparation records, a test procedures review, review and analysis of physical evidence at the site, and interviews of mishap witnesses. In addition to these activities, an SwRI team was allowed to study the site and collect data related to the distribution of debris caused by the mishap. Data collected included the type, size, and origin of debris, along with the impact characteristics and angles of debris throw. Although all identifiable motor casing parts were previously removed from the site, SwRI was provided with a missile map (shown in Figure 6) showing locations of retrieved motor casing fragments (numbered circles) and unburned propellant (circles with an "X" in them). SwRI also used post-mishap photographs (including aerial shots) to help summarize observations on debris and other physical evidence or damage indicators noted during the site investigation.

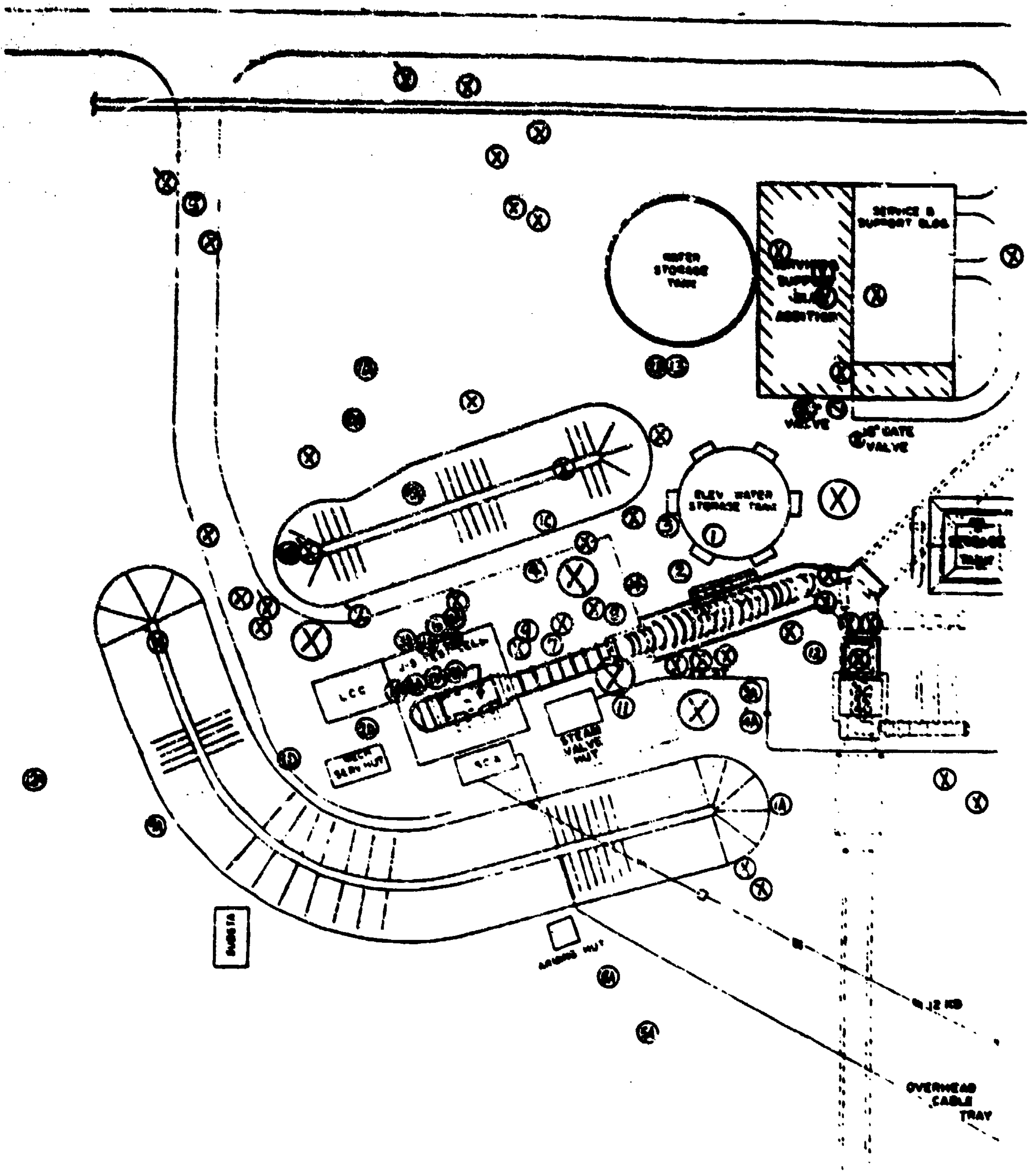


Figure 6. Missile Map Showing Motor Casing Fragments and Unburned Propellant

The hazardous zones predicted for a 20,000 lb TNT equivalent propellant detonation are shown in Figure 7A. The limit distances indicate the threshold of hazardous fragment density, defined as more than one fragment with kinetic energy greater than 58 ft·lb per 600 square feet. Impact locations of a few of the larger cell and building debris from the mishap are shown in Figure 7B. The location of the impacts furthest from the test cell in each zone are indicated on the figure. Note that these are locations of single fragments and do not correspond to the limit distances for hazardous fragment density for the mishap. The hazardous density for the mishap was limited to the bermed J-5 area.

4.0 MISHAP DEBRIS/DAMAGE ANALYSIS

Observations of debris scatter at the mishap site revealed heavy concentrations of debris in directions normal to the test cell enclosure building, establishing new evidence of the zone concept discussed in the J-6 debris study (Reference 1). Figure 8 illustrates these observations. In addition to providing general debris distribution information, the size and position of some of the major debris and the shape and number of motor casing fragments provided physical evidence of the type of explosion which occurred in J-5. Other observed damage indicators were also used to determine the nature of this mishap.

Observations of the test cell breakup pattern and the large size of test cell pieces examined on the initial trip around the site indicated the failure event may not have been a detonation, even though the propellant in the motor being tested was Class/Div. 1.1 (mass detonating) propellant. Also, the small amount of unburned propellant scattered about the site (see Figure 6) and the varied sizes and shapes of motor casing pieces collected earlier did not seem to agree with the initial premise that a detonation had occurred. The difference between a deflagration and a detonation, as it pertains to the J-5 mishap, is that a pressure pulse for a deflagration would be characterized by a smaller peak pressure and a longer duration than the pressure history for a detonation. However, the impulsive load on the test cell and on the structural members of the enclosure building could be just as great. With a

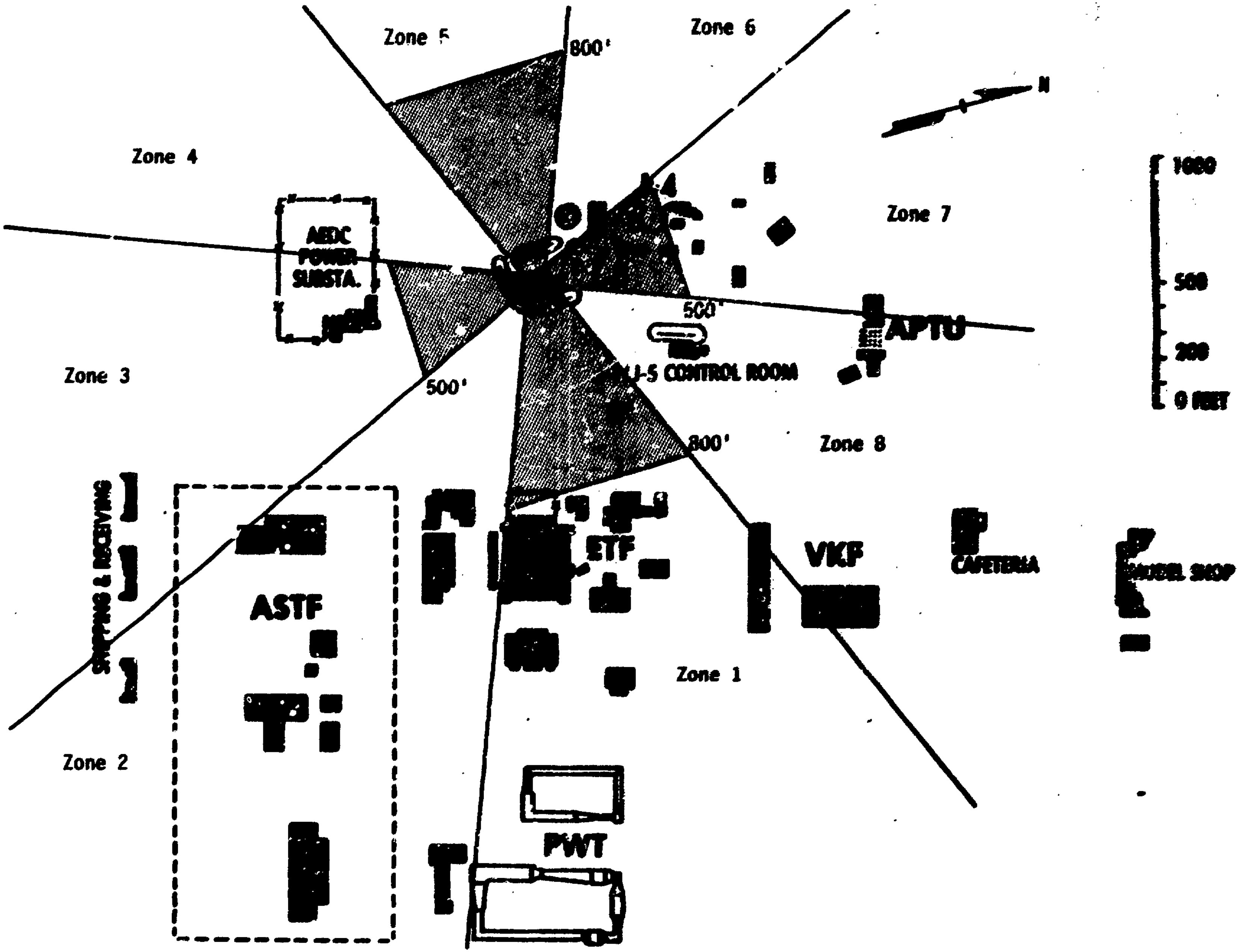


Figure 7A. Hazardous Debris Areas for a 20,000 lb TNT Equivalent Detonation

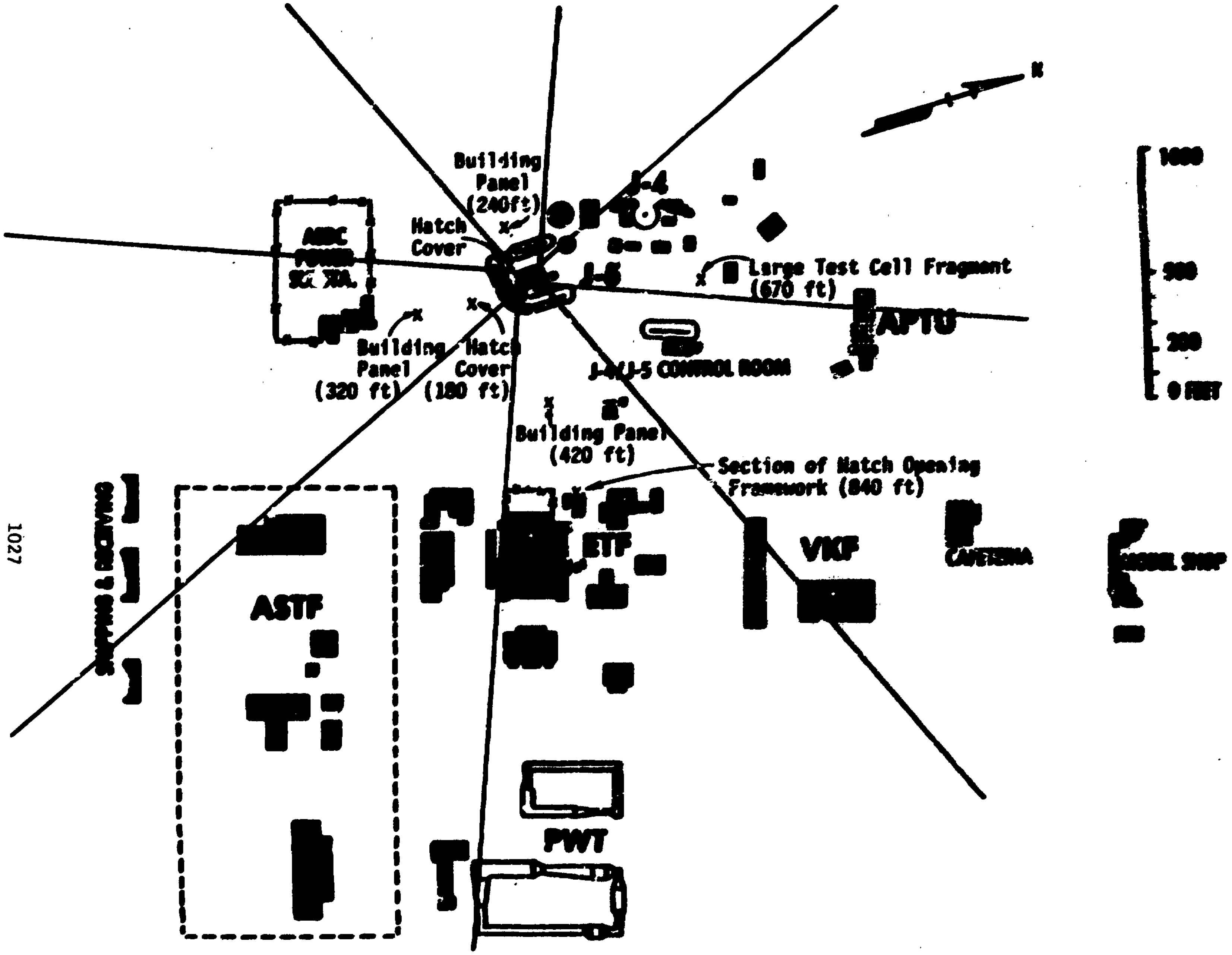


Figure 7B. Major Debris Impact Locations Following J-5 Mishap

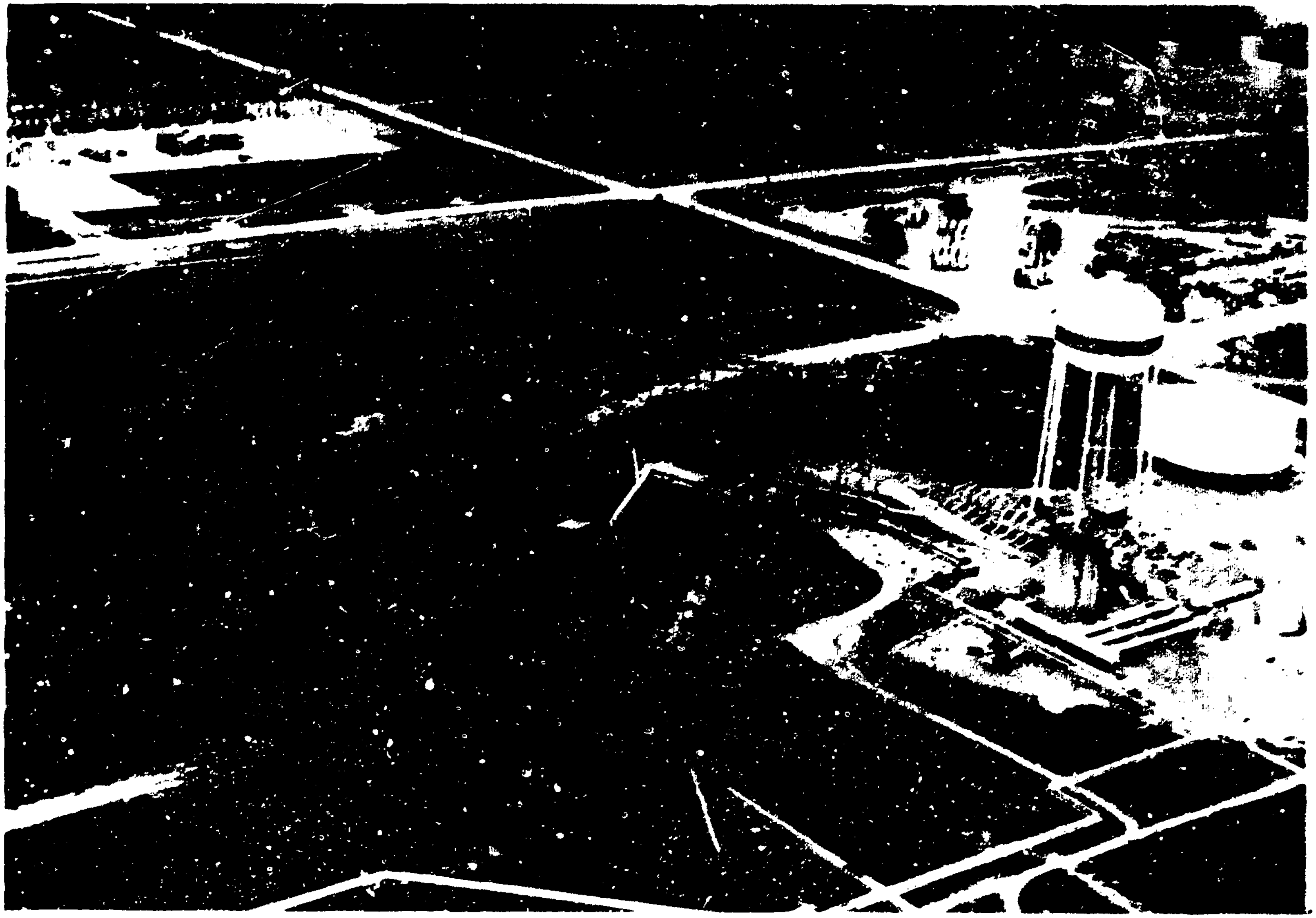


Figure 8. Mishap Debris Distribution

detonating motor, the casing would tend to break into a large number of small fragments. The casing pieces recovered at J-5 were not characteristic of a detonating motor. Further analysis of the other physical evidence noted in the investigation lends credence to a deflagration occurring in the motor.

Calculations were made to define the mishap sequence of events and to confirm the amount of propellant involved in the final event. The approach taken was to assume the reported conditions of the motor just prior to failure were accurate and to calculate debris velocities and ranges and impulse deflections based on a detonation in the motor. Assumed initial conditions at failure were:

- the 1100 lb of propellant in the motor was equivalent to 1375 lb of TNT,
- the motor had a diameter of 92 in. and a length of 125 in.,
- the motor casing weighed approximately 1500 lb,
- the steel test cell had a 16 ft diameter, a length of 50 ft, and a thickness of 0.5 in.

Results of the calculations were then compared with actual observations (measured distances, deflections, etc.) to determine the nature of the mishap.

5.0 CONCLUSIONS - SEQUENCE OF EVENTS

SwRI was doing an analytical distribution study for the J-5 test cell at the time of the mishap. Collecting data on the distribution of debris following the accidental motor failure at J-5 proved to be very useful, as it provided supporting data for the debris zone theory as presented in the J-6 study (Reference 1).

Once at the site, as much data as possible were gathered in the time allotted, including not just debris range and scatter angles, but also any other blast damage indicators or physical evidence of the type of explosion which had taken place in J-5. Based on observations, the test cell appears to have ripped open into a few very large fragments. This fact along with the small amount of unburned propellant (10 lb) scattered about the site and the characteristics of the recovered casing fragments indicate the mishap involved only a portion of the 1100 lb of propellant present in the motor at the time of failure, and a complete detonation of the remaining propellant did not occur.

Based on the breakup of the motor casing and distribution of casing fragments, SwRI believes something less than a complete detonation occurred near the nozzle which caused a dynamic rupture of the motor casing and subsequent release of unburned propellant into the cell. The further confinement of the propellant within the cell and the increase in propellant burn area caused a greater pressure buildup than the diffuser could handle, resulting in the following events which are relevant to the distribution of debris:

- The cell burst upon failure.
- The pressure buildup caused the two large hatch covers to be projected at high trajectories away from the cell.
- The cell endcaps blew off.
- The cell ripped open on the west side when it struck a stair railing producing several large fragments.
- The east side of the cell was deformed outward by the impact of motor casing pieces and blast and was deformed inward when it struck a bracket on the seismic mass.
- Unburned propellant was expelled from the cell.
- Blast loading inside the enclosure building blew out the metal wall and roof panels.

All analysis of the debris throw and observed damage indicators supports this theory. One of the most important lessons to learn from the J-5 mishap is the recognition of the types of events possible during a test of a motor containing Class/Div. 1.1 propellant and the severity of either a deflagration or a detonation. The observations of debris distribution and blast damage can be applied to the siting of similar test facilities in the future.

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THE INCIDENT OF THE L&N TRAIN MISSILE HARDWARE LADEN FIRE

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ABSTRACT

This report describes the railcar fire that destroyed the Ready Service Ring (RSR) used in the Mk 26 Missile Launcher System. Events leading to and during the railcar fire are given in a technical manner. The incident was tried in Federal Court, but the United States settled out of court for $1.4 million. The initial offer from the railroad was $2500.

INTRODUCTION

During the night of 13 September 1981, a fire involved a six-missile RSR section, associated hardware, and packaging material that were loaded on a DODX 39598 flatcar. The description of the events that led to this train fire is based on various sources of information. The "sources" were not always in agreement.

The cause of the fire was agreed to by most experts from both sides (the United States and the railroad). The fire was caused by ignition of the wood floor by the hot metal sparks coming from overheated brake shoes and wheels. How the brake shoes and wheels became overheated was the technical question in the case. (The legal portion of the case is not part of this report.) The two possible sources of hot brake shoes and wheels were: (1) a hand brake that was left on at the last point of departure for this train; or (2) a hidden defect in the air braking system on this car. The position of the United States was that a hand brake had been left on, and the position of the Louisville and Nashville (L&N) railroad (now Seaboard) was that of a hidden defect in the car air-braking system. The plausibility of other events causing the car fire was considered. These events were evaluated and removed from further consideration because of the fire pattern under the car, condition of the heated brake shoes and wheels, train travel pattern, and time of day. (For example, spontaneous combustion and sabotage were considered as possible events and eliminated.)

A brief background to the series of events prior to and during the car fire will be given, followed by a limited discussion of the two different theories for the ignition of this fire, and a story of what may actually have taken place the night of the car fire. The story is based on documents, statements, depositions, and train records and charts, etc., from L&N railroad. When a conflict arose, actual records and charts were considered first, then early statements, and last depositions.

EVENTS LEADING TO AND DURING THE RAILCAR FIRE

The Mk 26 Missile Launcher System was loaded on seven DODX flatcars at the Northern Ordnance Division of FMC Corp. in Fridley, MN, for a final destination of Pascagoula, MS. The seven DODX flatcars left Minneapolis on about 6 September 1981, and arrived at the last departure point prior to the fire on 13 September. This last departure point was the Howell yard, Evansville, IN, where these seven DODX flatcars were part of Train 769 arriving from Woodlawn IL. At the Howell yard, one DODX flatcar was separated from the other six DODX flatcars. This separation occurred between a DODX flatcar with a high, wide load and DODX 39598. The DODX flatcar with the high, wide load was to become a part of a different train consist going a different route to the same final destination. The end car was now DODX 39598. During the make-up of Train 717, the hand brake was set on this end car to prevent car movement in this part of the consist. These six DODX flatcars became part of Train 717, which comprised 149 cars; DODX 39598 was the 97th car ahead of the caboose. The DODX 39598 flatcar was a 50-foot car equipped with roller-bearing axles, high-phosphorus cast iron brake shoes, and a wooden floor. There were spark shields over the first axle only. The six-missile RSR section was located at the B end of the flatcar, which was covered with an 8-foot-wide, 10-foot-high, 32-foot-long plywood box. Two or four small boxes were located at the A end of the car; these contained miscellaneous machinery. These small boxes did have wooden bottoms and they were on wooden pallets for ease of fork lift handling. The big box was attached to the car floor; except for a layer of Kraft paper, no other material was used for the bottom. The make-up of Train 717 with its 149 cars was completed by 7:15 p.m. on 13 September 1981. Train 717 left the Howell yard at 8 p.m. on that day.

The course of Train 717 as it headed south from the Howell yard was determined from tables of times of Train 717 on 13 September past stations from Evansville, IN, to Nortonville, KY; from the CTC train graph and dispatcher's log, and from calculated speeds derived from the times. For comparison, data were collected on three other trains that were in that track area during the night/morning of 13-14 September 1981. Trains 717 and 2/769 were headed south, and Trains X8025N and 792 were headed north. The data on the four trains are given in Table 1. A plot of progress (time versus distance) of the four trains is shown in Figure 1. There are two track paths at the Atkinson location; one path goes through the Atkinson (Trident) switch, Earlington, and the Morton cutoff, whereas the other path goes through the Atkinson cutoff, the Atkinson yard, and the same Morton cutoff. Train 717 is a daily southbound train; for comparison, Train 717 of 17 September 1981 is also plotted in Figure 1. Table 2 covers the events that took place during the time that the Train 717 of 13 September went from the Howell yard to the switches at Kelly.

TABLE 1. Time-Distance of Trains, 13-14 September 1981.

Yard/location	Mile post	Time that caboose opened switch			
		717	X8025N	2/769	792
Howell	321.8	8:00 p.m.		9:50 p.m.	11:55
Henderson	31.7	8:16		10:19	11:05
Rankin	309.55	8:27.5		10:22	10:55
Robards					
North end	302.2	8:36		10:34	10:42
South end	300.6	8:37.5		10:36	10:30.5
Breton					
North end	293.5	8:50.5		10:50	9:56.5
South end	292.2	8:53		10:52	9:56
Hanson					
North end	282.6	9:04.5		11:08.5	9:42
South end	281.3	9:06		11:10.5	9:41
Arklow	277.5	9:12		11:18.5	9:34
Atkinson					
Trident	276.6	9:16.5		---	---
Cutoff	276.?	---		11:40	9:31
Earlington					
North end	272.7	9:23.5		---	---
South end	271.0	9:26.5		---	---
Morton cutoff	268.0	9:31			
	267.0	9:32		11:53.5	9:16
				11:54.5	9:15.5
Nortonville					
North end	266.2	9:33.5	12:02 p.m.	11:56	9:12.5
	264.?	9:37.5	11:38	12:00	9:08
ICG crossings	(264.2)	9:37.5	11:36	12:00	9:07.5
	264.?	9:41			
Romney					
HBD	262.0	10:30*	11:33*	12:04*	9:05*
Siding	260.4	~10:32*	11:30*	12.06*	9:02*
Crofton					
North end	254.1	11:15	11:20	12:18	8:52
South end	252.7	11:17	11:08	12:20	8:50
Kelly					
North end	248.4	11:23.5	10:16.5	12:27	8:43
South end	247.2	11:25.5	10:15.5	12.29	8:42

Notes: The term yard or location is the name of the yard and/or switch location in regard to a given mile post. Track switches are closed by the train engine when first contact is made and are reopened when the caboose (last car) has crossed the switch. The data are recorded on a time-driven recorder with an event marker for each switch. There can be more than one switch at a given location. The switches located at the ICG crossing are very close together (estimated at about 0.1 mile).

*Reported by the conductor of Train 717 as the time of the incident; assumed to be the time the caboose passed the activated Romney hot box detector (HBD). L&N claimed no knowledge of the fire before this.

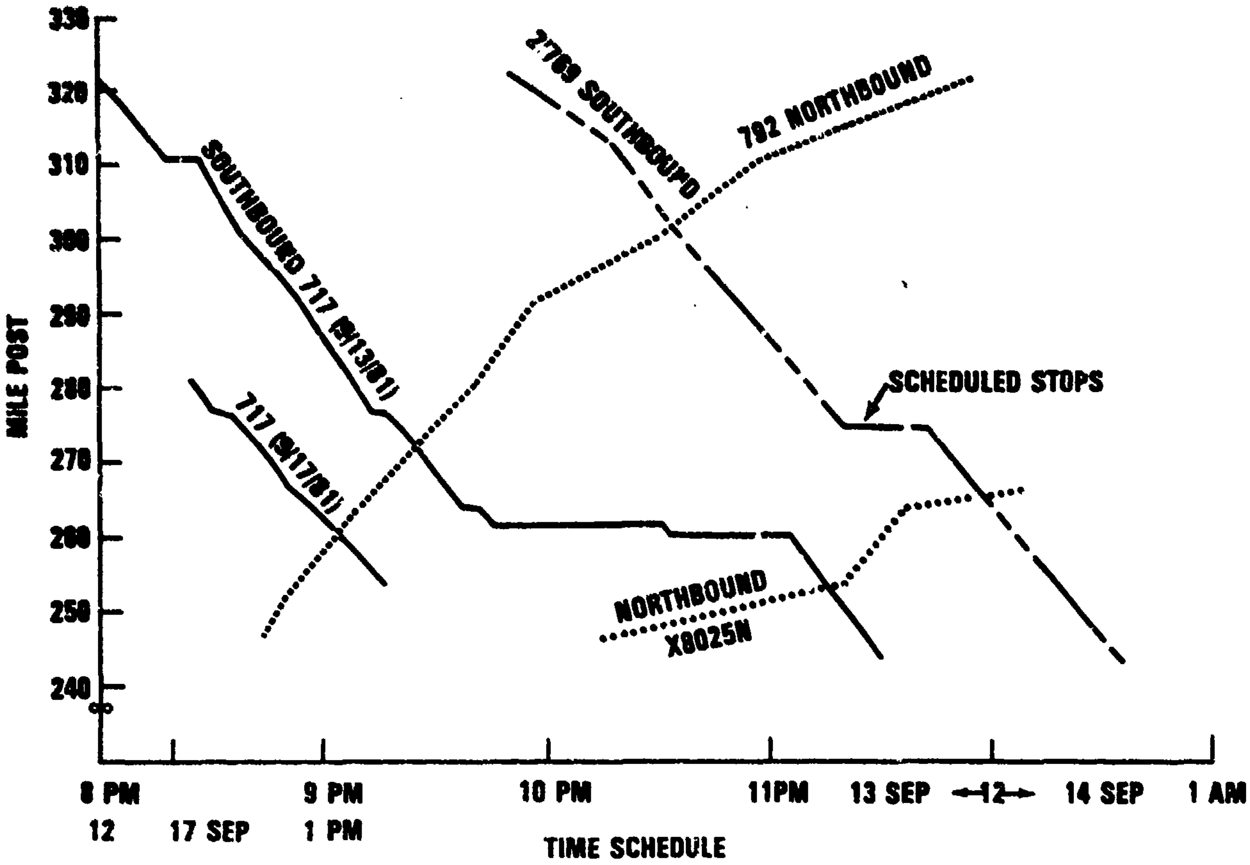

Figure 1. Five Train Time-Distance Processes on 13-14 and 17 September 1981.

TABLE 2. Time-Distance of Trains, 13-14 September 1981.

Location	Mile post	Time		Station log, sheriff dept & L&N personnel call/time/code	Reference
		Train 717	Train delay		
Howell	321.8	8:00 p.m.		(Operator: Prow)	
Henderson	311.7	8:16			
Rankin	309.5	8:28	5 min		Fig. 1
Robards	300.6	8:38			
Breton		Breton		Breton	Breton
North end	293.5	North end		North end	North end
South end	292.2	South end		South end	South end
Hanson	281.3	9:06		Squad 4/8:40/10-8 Squad 4/8:43/10-97 Squad 4/9:13/10-98	
Ar[illegible]low	277.5	9:12			
Atkinson	276.6	9:12			
Earlington	271.0	9:26			
Morton's	267.0	9:32		Rash/~9:32/717	Rash
Nortonville	266.2	9:34			
Two ICG crossings	264.2	9:41	3 min	(717 stopped/backed up)	Table 1
				Squad 4/9:45/10 10	
				717/~9:55/fire call	Dispatcher
				MGFD/10:07/call	
				MGFD/10:10/10-8	
				Rash/~10:24/10-97	Rash
				MGFD/10:25/10-97	
			45 min		Fig. 1
Romney					
HBD	262.0	10:30			Conductor
Siding	260.4		62 min		Conductor
			40 min		Dispatcher
		~10:32	33 min		Fig. 1
Crofton	252.7	1:17			
Kelly	247.2	11:26		MGFD/~11:30/X8025N	MGFD
				MGFD/11:56/10-10	
		12:00		(operator/Howell)	

Note: The Hopkins County Sheriff Department operator was H. Prow until midnight and C. Howell after midnight. Conductor is the Train 717 conductor. MGFD is Morton's Gap Fire Department.

APPLIED HAND BRAKE VERSUS DEFECTIVE CAR AIR CYLINDER THEORIES

As background information on the two possible causes of the fire, a joint mechanical inspection was made on the DODX 39598 railcar by both the parties on 21 September 1981. Prior to this meeting, this DODX railcar was moved back to the Howell yard, and the cargo was transferred to another flatcar for shipment back to FMC Corp. The joint inspection on the car in question after the fire revealed the following information, given here in brief:

1. The slack adjustor was inoperative.
2. Brake shoes at all locations were worn to condemnable limits.
3. The AB reservoir was leaking in the center.
4. Angle cocks at the A&B end were leaking.
5. The combination cutout cock and dirt collector was leaking.
6. Wheels at all locations had been hot about 2 inches into the wheel plate.
7. The deck was completely burned from the car.
8. Piston travel was 9½ inches; during an emergency application and a 20-pound reduction, the piston travel was 6¼ inches. The car brake system requires 5 inches.
9. The last IDT of DODX 39598 was 7/21/81, B&N railroad. The car did not pass L&N personnel on 21 September 1981 because of excessive leakage.
10. The car was COT&S per Rule 2 of AAR Interchange Rules.
11. Inspection of DODX 39598 revealed two spark shields in place. (Cars ordered redecked on or after 1 August 1973 require spark shields.)

These statements made at this early inspection were not fully accepted by both parties.

The argument that L&N proposed was that a "hidden defect" was the cause of the fire on this car, and this defect was in the air brake system of the DODX 39598 car. For the defect to affect the braking system on this car, the train air braking system would have to be activated at some point in time after the train left the Howell yard and before it reached the Romney HBD. According to the deposition of the train engineer, he did not use, or was not sure that he used, any air reduction during the trip between Howell yard and the point at which the fire may have started. The use of the train's dynamic braking system in this case would have been sufficient to control the train speed.

Later, L&N claimed that heavy braking occurred after mile post 275, causing brake shoe sparking and consequently the car floor fire. L&N suggested that the heavy brake shoe sparking activated the Romney HBD. L. Rash (L&N Railroad employee and also deputy sheriff that night) claims he saw every car as the train went by mile post 268 (Morton's Gap). He further claimed that he did not see any car fire or any wheel sparking on the train. He estimated the train speed at 40 mph. The train conductor reported a train speed estimated at 40 mph. The average speed was 36.7 mph for Train 717 from Atkinson (mile post 276.6) to Nortonville (mile post 266.2). For comparison, another Train 717 on 17 September 1981 also averaged 36.7 mph when covering the same distance (see Figure 1).

Train 717 of 13 September 1981 stopped after passing through the two switches at the ICG crossing (mile post 264.2) and backed through one ICG switch, then cleared the switch at 9:41 p.m. According to the L&N records, this train did not clear the Romney HBD (mile post 262.0) until 10:30 p.m. A fire call was made at 9:55 p.m. from the Atkinson dispatcher to Train 717. The Hopkins County Sheriff Department contacted the Morton's Gap Fire Department (MGFD) at 10:07 p.m. with a message to go to the Romney railroad, "car on fire." MGFD was on its way at 10:10 p.m. and arrived at 10:25 p.m. L. Rash and an L&N truck with yellow flashers and crew were also at the Romney crossing. L. Rash also claims that he heard over the radio the call from the train conductor about a fire having been caught by the hot box detector and calling the operator at the Sheriff Department. He said the operator was C. Howell; however, Howell did not come on duty until after midnight.

The unreleased hand brake theory is based on severalfactors, which are as follows:

1. The DODX 39598 car had been traveling for several days with no apparent air brake problems; then, suddenly, would it be likely to have a massive air leak problem on an apparent single air brake application.
2. The DODX 39598 car was the end car to a string of cars being put together for Train 717 in the Howell yard.
3. The hand brake is usually set on the end car.
4. The literature has articles on the consequences of unreleased hand brakes on freight cars. The probability of occurrence is up to 30%.
5. Train speed and sufficient brake horsepower are needed to cause heavy brake shoe sparking and ignition of the car floor.
6. The B end of the car is at the rear of the car and the sparks from the first axle are directed downward, away from the floor; from the second axle, the sparks are directed upward into the floor; from the third axle, downward, as with the first axle; and from the fourth axle, upward, as with the second axle. The second axle would help ignite the floor at the rear end of the train.

7. The initial train speed after leaving the Howell yard speed limit of 10 mph was estimated in excess of 45 mph.

8. There apparently was a train stop for about 7 minutes between Henderson and Rankin. It is speculated that heavy wheel sparking was noted, and the hand brake was released. The floor fire could already have started. Ignition of the floor can occur in a few minutes.

9. A train speed in excess of 50 mph at times would have helped the floor fire under the car to continue.

10. The time needed to burn through the floor is about 10 minutes.

1. The fire under the car tends to die out in about 20 minutes. The fire would spread on top of the car floor and should spread from side to side in 15 to 60 minutes. Since there is no floor to the big box at the rear end of the car, once the fire reached the walls of the big box, then it would spread very quickly inside the big box. The big box was made of very heavy plywood (estimated at 1¼ inches thick, and the fire inside would not be visible on the outside.

12. As Train 717 passed by L. Rash at mile post 268, the fire under the floor had died out, but the fire inside the big box, although continuing, was not visible, nor was it visible at the A end of the car because the wood pallets under the small boxes would have blocked Rash's view of the fire.

STORY OF THE 717 TRAIN FIRE OF 13 SEPTEMBER 1981

Train 717 should have left the Howell yard at 7:45 p.m., but did not leave until 8:00 p.m. The train moved at 10 mph until it left the limits of the Howell yard. The train then traveled at the maximum speed limit until leaving the Henderson yard. Apparently, the fire and sparks from the DODX 39598 car got somebody's attention, and the train was stopped for a few minutes to release the hand brake. Apparently, a fire was noted, since an L&N truck was at the fire site and the train engineer changed the train path to go through Earlington instead of going through the yards at Atkinson. The yardmaster at the Atkinson yards was expecting this train and called the train to determine where it was. It may be assumed that the train engineer knew that a car was on fire and that he called a fellow L&N employee, L. Rash, to do a visual inspection of the train as it went by mile post 268. L. Rash did not observe any fire, since it was hidden inside the big box and by the pallet blocks under the small boxes. The train went through Nortonville and stopped just past the ICG crossing. A fire at the rear end of the car had already been reported at this time. The fire in the big box was fought by L&N personnel from the L&N truck, by L. Rash, and by others. The fire in the big box was reduced, and the train proceeded, with the conductor calling the Sheriff Department for help and stopping the train when the burning car would be at the Romney railroad crossing. This fire was at the A end of the car where the small boxes were located. This fire was put out by the MGFD, and it assumed that, since the fire had not reached the big box, the big box was not involved. When the car was seen again, the fire in the big box had consumed the rest of the car.

SUMMARY

The United States case on the technical question of braking and hidden defect of DODX 39598 was strong and was further strengthened by the transcripts of L&N's experts. Had the court case continued, the United States position would have shown that L&N's contention of a fire stemming from stuck brakes after the engineer's use of the airbrakes to slow down at Sebree (mile post 297) was completely unreasonable. This L&N position was not in line with the opinion of its own experts, since conditions were asserted that did not exist on Train 717 at the night of the fire. The out-of-court settlement of $1.4 million, although far larger than the original offer of $2500, was less than the estimated $6 million loss. A lesson learned in this case is that the initial investigation, which dealt primarily with the burned car, should perhaps have emphasized what happened the night of the fire.

ACKNOWLEDGMENTS

The authors would like to thank Alfreda Bennett, Diane Ennist, Dan McMullin, and Irene Hirata (formerly NAVSEA) from the Department of Justice for the opportunity to be part of the challenge in this court case.

THE INCIDENT OF THE L & N TRAIN MISSILE HARDWARE LADEN TRAIN

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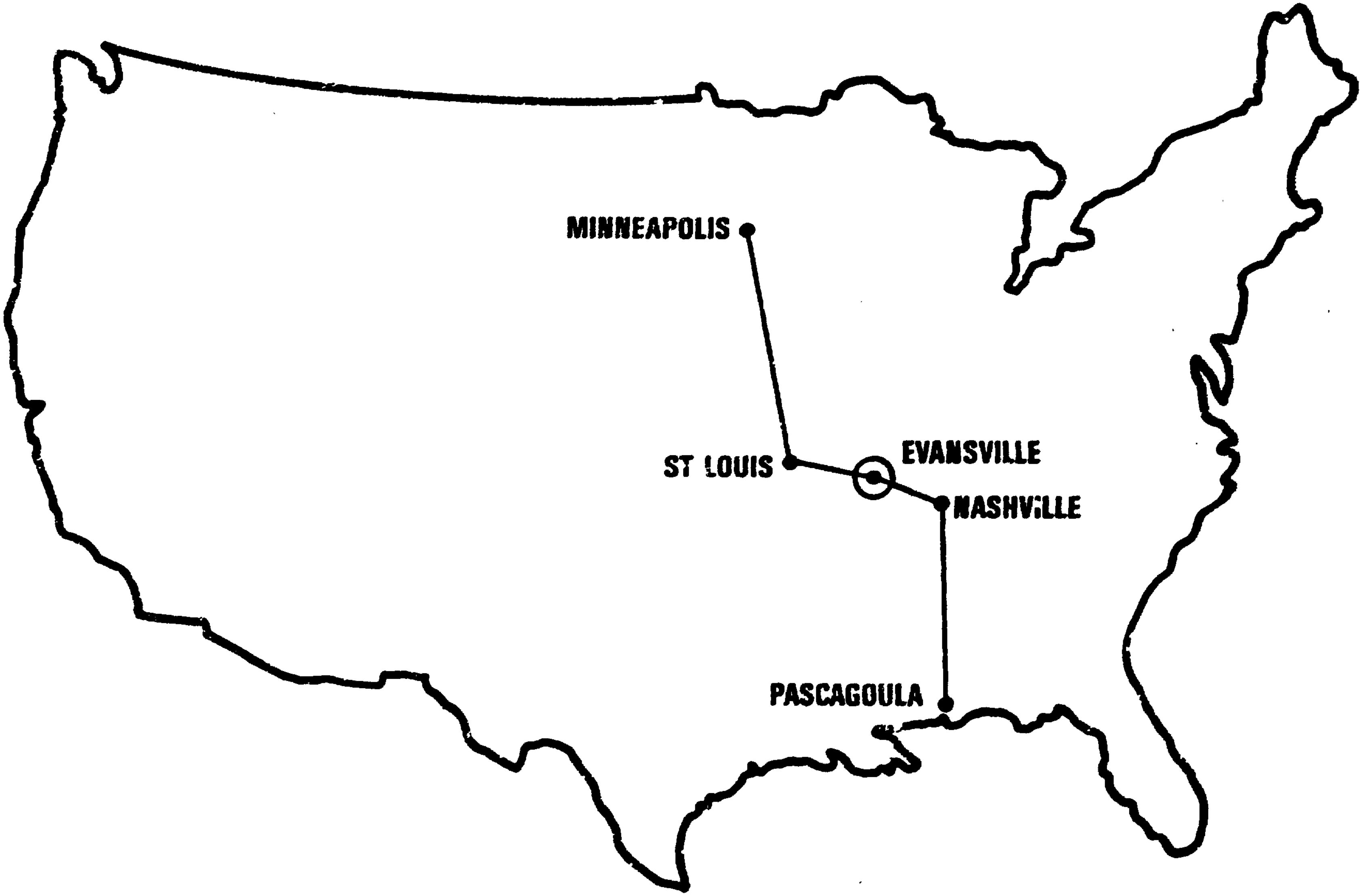
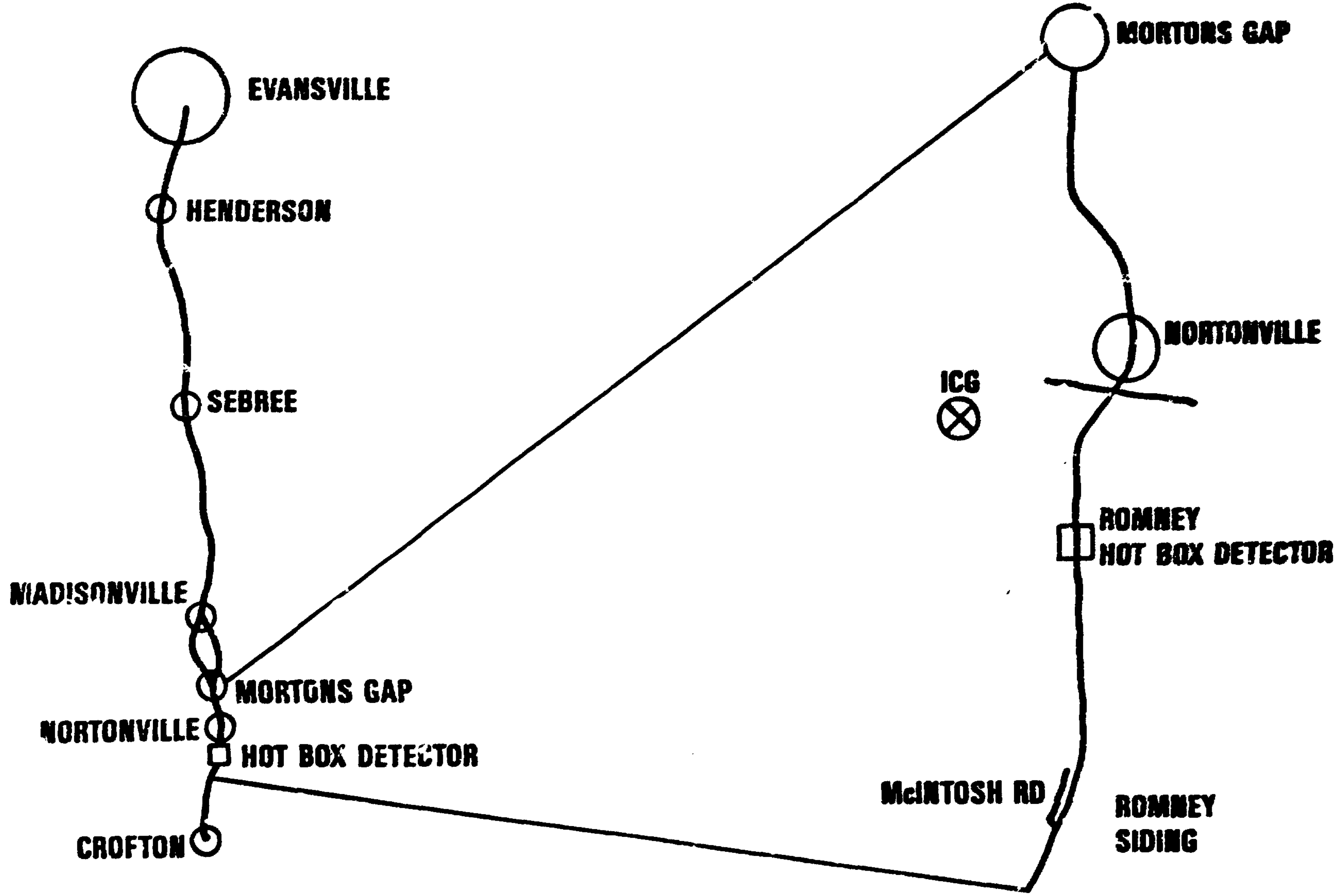
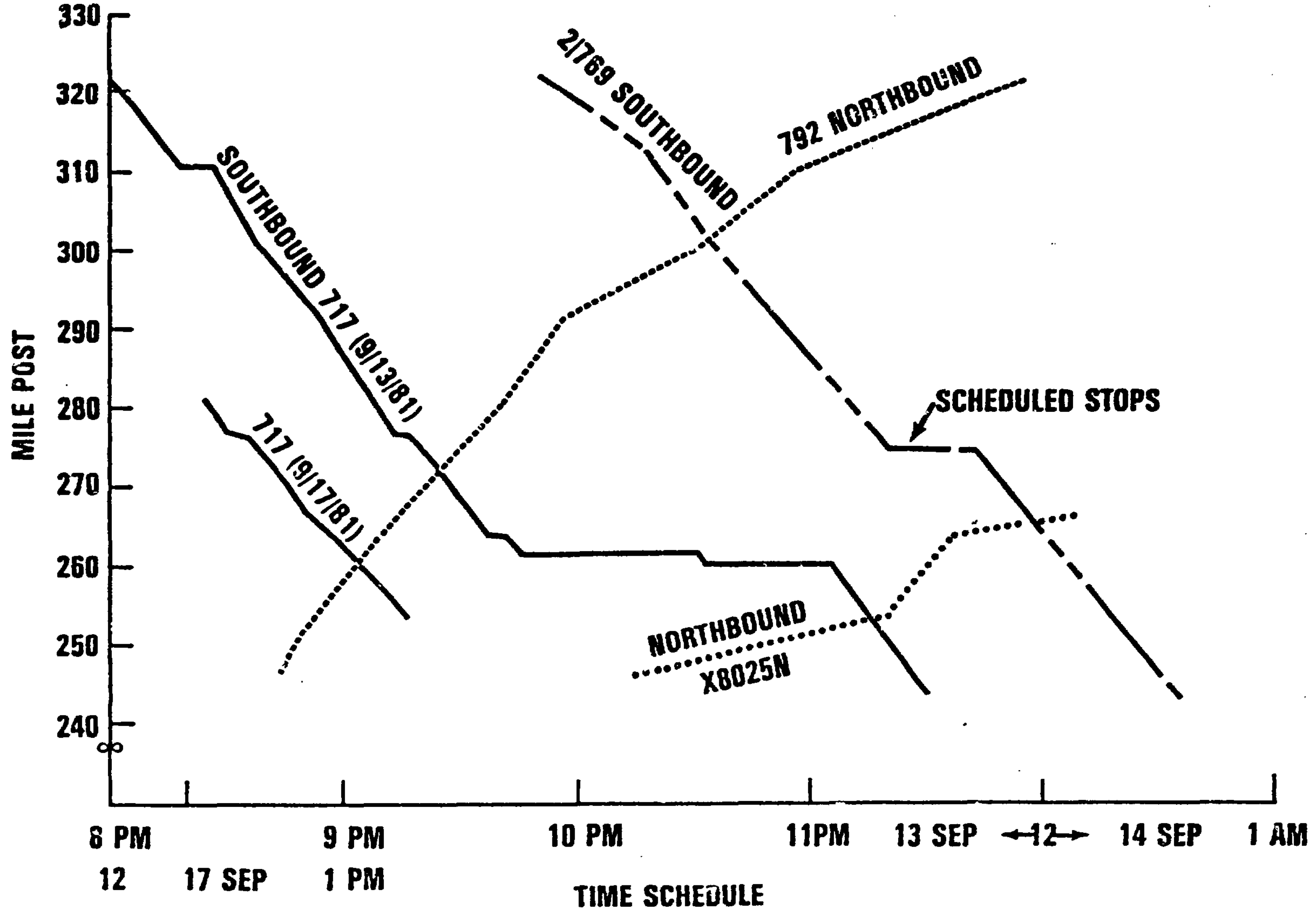
TRAIN ROUTE MK 26 MISSILE LAUNCHER



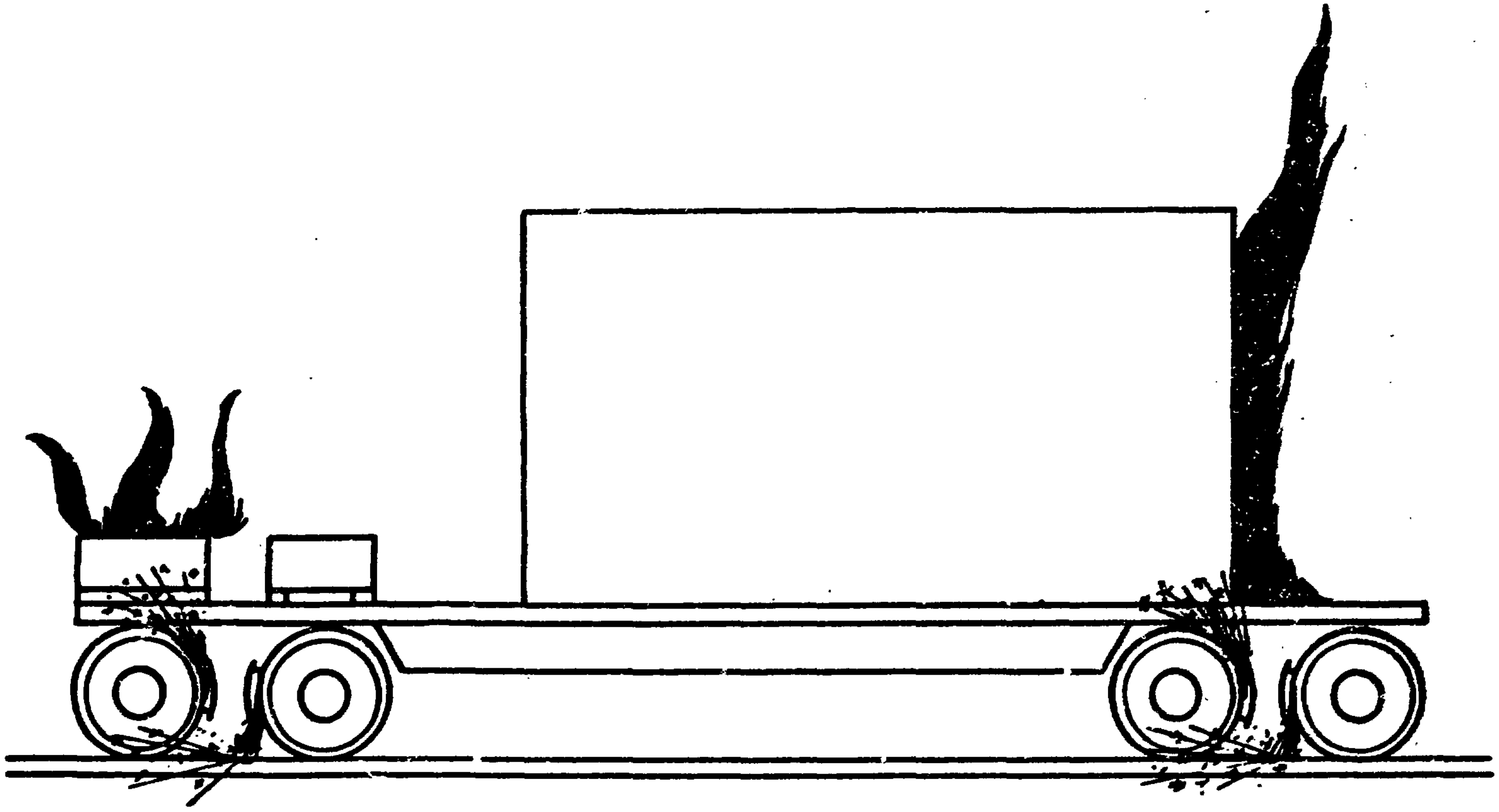
TRAIN ROUTE OF DODX 39598 FLAT CAR



FIVE TRAIN TIME – DISTANCE PROCESSESS ON 13/14/17 SEPT 1981



DODX 39598 CAR FIRE



A REVIEW OF RECENT LIGHTNING-RELATED MAGAZINE DEFLAGRATIONS

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Abstract

This paper reviews the similarities between the above-ground magazine deflagration of 12 July 1985 at the Naval Surface Weapons Center, Dahlgren, Virginia and those of 22 February 1979 and 13 September 1984 at Lake City Army Ammunition Plant (LCAAP), Missouri. Subsequent investigation of the incidents concluded that each was the result of a lightning discharge. In each case, lightning was "in the area" but in none of the cases was a direct discharge in the immediate area confirmed by an eyewitness.

"LeverPak®" fiberboard drums were being stored in each of the magazines that deflagrated. In the Dahlgren incident, it was concluded that the fire originated in an area in which a majority of LeverPaks were stored. Navy "LeverPak®" drums were subjected to both direct and radiated ESD impulses with peak voltages of up to 400kV. Army "WeatherPak®" drums ~~provided by LCAAP~~ were subjected to similar radiated ESD impulses. Test results suggest that internal arcing was fusing the top and bottom chimes to the aluminum vapor barrier. This arcing could ignite any flammable vapors or explosives dusts that may be in the vicinity of the arc. "Navy" drums differ from "Army" drums by an internal 1-inch aluminum foil strip bonding the top and bottom chimes.

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TABLE OF CONTENTS

1. INTRODUCTION

On 22 February 1979 and 13 September 1984 separate above-ground smokeless propellant magazines in the 19-Area at Lake City Army Ammunition Plant (LCAAP), Missouri deflagrated as a result of lightning activity[1][2]. The 19-Area magazines are located in a valley on a dry lake bed. The magazines are wood frame structures built on a concrete deck with corrugated asbestos siding and a flat tar roof. They were constructed in 1941 and were equipped with an integral lightning protection system [3] which received an Underwriters Laboratories Master Label in 1947[1].

On 12 July 1985 Magazine 1L4 at the Naval Surface Weapons Center Dahlgren Laboratory deflagrated consuming its entire contents of 170,900 pounds of smokeless propellant. Propellant grains stored in the magazine ranged in size from 0.10 inches x 0.04 inches (20mm) to 1.20-inches x 0.50-inches (for 8-inch rounds)[4]. Like the Lake City Army Ammunition Plant 19-Area magazines, NSWC/Dahlgren Magazine 1L4 was an above-ground magazine (Class II as defined in NAVSEA OP-5, paragraph 4.9).[5]. However, it was constructed of steel reinforced concrete walls sitting on an elevated concrete deck with steel roof and ceiling frames and corrugated asbestos roof and ceiling. A mast-type lightning protection system was installed in 1941 (at the time of magazine construction). The height of the masts was not adequate to provide a "zone-of-protection" as currently required for these type structures [5][6][7][8]. However, the mast-type system did meet the zone-of-protection requirements in effect at the time of installation[9][10].*

None of the lightning protection systems for any one of these structures met current lightning protection system requirements. Specific deviations for each system will be discussed herein in later sections along with any lessons learned.

The NSWC incident investigation identified a potential risk associated with the design of one of the bulk propellant containers stored in the magazine[11]. This was thought to be a major contributor in the deflagration [4][12]. A similar configuration of these containers were stored in both Lake City

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* Reference [10] was the oldest copy of <u>BUORD OP-5</u> accessible to the NSWC Investigation Team. The edition in effect at the time of construction was released in 1927. Since the June 1944 Revision to <u>BUORD OP-5</u> reflected the most stringent zone-of-protection requirements in effect at the time it is highly probable that the system met all previous zone-of-protection requirements.

AAP magazines. High-voltage ESD tests were conducted on both configurations of "LeverPak" containers. These tests are discussed in Section 5. They indicate that the resistance between the top and bottom chimes of the LeverPak containers decreases when subjected to either direct or indirect current impulses. Potential arcing can ignite explosives dusts or gases trapped in the containers. As a result, the Naval Sea Systems Command has directed that LeverPak-type containers shall not be stored in Class II magazines[13]. Justification for this decision is also forwarded in Section 5.

2. BACKGROUND

2.1 HISTORY

2.1.1 LAKE CITY ARMY AMMUNITION PLANT (LCAAP) 19-AREA MAGAZINES

The 19-Area magazines at Lake City Army Ammunition Plant are wood framed, corrugated asbestos-sided flat roofed magazines constructed in 1941[1]. An integral lightning protection system was installed just after construction which received an Underwriters Laboratories Master Label dated 1947. A hot air (steam) heating system was installed in 1953[2]. The ordnance grounding system was also installed at that time (identified as static ground bus bar in the Army Board of Investigation Report on LCAAP Magazine 19L[2]). The ordnance ground system consisted of a 1-inch by 1/4-inch copper bus bar completely encircling the interior of the magazine 7 feet above the conductive floor. A static grounding system consisting of a conductive deck was also installed in the 19-Area magazines. The static grounding system was grounded independent of the lightning protection system. Army Explosive Safety Standards in effect in 1953 were not available, but Navy Standards in effect at the time did not require that the lightning protection system be interconnected to any other grounded systems[10]. In 1978 the magazines were reroofed and the lightning protection system was modified to provide 24-inch air terminals vice the 18-inch terminals originally installed. No effort was made to bring the remainder of the system up to current standards.

The 19-Area magazines are located in a valley that was formally a lake bed. Plant production buildings are built on the hills surrounding the magazines. However, the magazines are prominent in the large flat area which makes them attractive lightning termination points. This is evidenced by a visual inspection of the magazines and cottonwood trees in the magazine area on 7-8 March 1986 revealing that both the trees and air terminals on the existing magazines had been struck by lightning[14]. Even though not specifically addressed in my final report [2], the author has noted this evidence and documented it in my trip report on the investigation (memo to files).

2.1.2 NSWC MAGAZINE 1L4

Naval Surface Weapons Center Magazine 1L4 was an above-ground, steel reinforced concrete magazine with a steel frame roof and ceiling that had four symmetrically spaced copper ventilators mounted on the crest of the roof. A mast-type lightning protection system was installed at the time of construction (1941). No utilities had been installed in the magazine (electricity, water, fire alarm, etc.).

An ordnance grounding system was installed at the time of construction. Earlier in the summer of 1985 the ordnance grounding system had been modified as a result of an informal suggestion from a Department of Defense Explosives Safety Board Inspection Team.

The steam heating system was bonded to and grounded through the static grounding system. *("ordnance bus bar" and conductive floor) which was grounded separately from the lightning protection system. However, the vent pipe was bonded to the lightning protection system at the roof level (possibly at the time of reroofing). The lightning protection and static grounding systems were bonded together only through this connection. The steam pipes feeding the magazines were not grounded except through the magazine's static grounding system[1].

2.2 Incident Details

2.2.1 Lake City AAP Deflagration

On 22 February 1979 and 13 September 1984 an above-ground magazine deflagrated at Lake City AAP. In both cases lightning activity had been seen in the vicinity of the plant but in neither case did an eyewitness see a strike in the magazine just prior to the event (although eyewitnesses to the event were questioned).

The 19-Area magazines were routinely checked by Lake City AAP security personnel. On 22 February 1979 Magazine 19L had been checked approximately 20 minutes prior to the deflagration and no abnormal conditions were noted. Some witnesses stated they had seen lightning in the immediate area but others had not. National Weather Service Severe Storm Warning Center in Kansas City, Missouri confirmed that lightning activity was within 30 miles of Lake City AAP at minimum. No direct strike to any of the magazines was witnessed that night[2].

On 13 September 1984, Magazine 19S had been checked by security personnel approximately 3 hours prior to the deflagration. Excessive interior temperatures were noted and reported to the night foreman. The equipment room was inspected approximately 2 1/2 hours prior to the deflagration and no abnormalities were detected. There was lightning activity in the area prior to the deflagration. Explosives operations had been shut down up until approximately 15 minutes before the deflagration was detected[1].

In both cases the magazines and their entire contents were totally consumed.

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* Unlike Navy documents, the Army Safety Manual [8] does not recognize an ordnance and static ground system. In discussing the Army grounding sytems the "ordnance bus bar" refers to the copper bus bar mounted on the interior wall of the magazine.

2.2.2 NSWC/DL Deflagration

National Weather Service weather radar echoes show that intense storm cells were beginning to build west of Dahlgren, Virginia as early as 0300 on 12 July 1985. Hail and severe thunderstorms were reported over a large area. Lightning activity was reported in the area as early as 0330[4]. Electric field mill recordings show that electric fields exceeded -5000 volts/meter as early as 0300.

Eyewitnesses report that the majority of lightning activity had passed over the Base. No cloud-to-ground lightning in the vicinity of the Base was reported immediately prior to the deflagration.
At 0503 on 12 July 1985, Magazine 1L4 deflagrated. Subsequent investigation revealed that the fire had probably started prior to 0500 in one of the containers and had propagated until some of the smaller grain propellants were ignited. These small grains burned at a much faster rate and was most probably the cause of the major deflagration that resulted in the loud report and fireball that went through the roof.

The magazine is located in the rear of Magazine Area 1. Security personnel do not normally check each of the magazines unless the gates to the area are found open. They are not allowed in the magazine areas when thunderstorms are in the vicinity. For this reason, the fire could have been burning for a long period prior to its detection. Based on the melting of a copper ventilator, zinc-coated steel pallets, and the warping of some beams in the roof frame it is expected the fire was burning for some 30 minutes prior to its detection.

Fire protection personnel responded to the report of the magazine fire but were not allowed into the area to fight the fire. The fire was allowed to burn itself out before anyone was allowed into the area. A number of "pops" were heard while the fire was burning; most likely due to the cookoff of the propellant in MK 7 containers. The entire contents of 170,900 pounds of smokeless propellant was consumed in the fire.

3. Lightning Protection

3.1 Lightning Protection Systems

3.1.1 Lake City AAP Systems Description

Integral lightning protection systems were installed to protect the 19-Area magazines at their time of construction (1941). Underwriters Laboratories Master Labels were acquired for these protection systems in 1947[1]. A steam heating system was later installed.

The steam heating system was bonded to and grounded through the static grounding system *("ordnance bus bar" and conductive floor) which was grounded separately from the lightning protection system. However, the vent pipe was bonded to the lightning protection system at the roof level (possibly at the time of reroofing). The lightning protection and static grounding systems were bonded together no other way. The steam pipes feeding the magazines were not grounded except through the magazines static grounding system[1]

The magazines were reroofed in 1978 and the 18-inch air terminals were replaced with 24-inch air terminals. No effort was made to the upgrade the remainder of the lightning protection systems to standards in effect at the time.

3.1.2 NSWC System Description

3.1.2.1 Primary Protection System

A mast-type system was designed for Magazine 1L4 in 1940 and installed in 1941. Mast heights were designed such that the tip of each mast was 59 feet above deck level. This is exactly twice the peak height of the structure (28 feet). The masts were spaced 32 feet from the corner of the structure.

The masts were interconnected by a 2/0 stranded copper-cable primary ground girdle. Figure 1 shows the location of this girdle and identifies the actual location of the 8 ground rods bonded to this primary girdle. The girdle was buried a minimum of 2 feet below grade.

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* Unlike Navy documents, the Army Safety Manual [8] does not recognize an ordnance and static ground system. In discussing the Army grounding systems the "ordnance bus bar" refers to the copper bus bar mounted on the interior wall of the magazine.

FIGURE 1 (a).

PRIMARY AND SECONDARY LIGHTNING PROTECTION SMOKELESS POWDER BUILDING (NO SCALE)

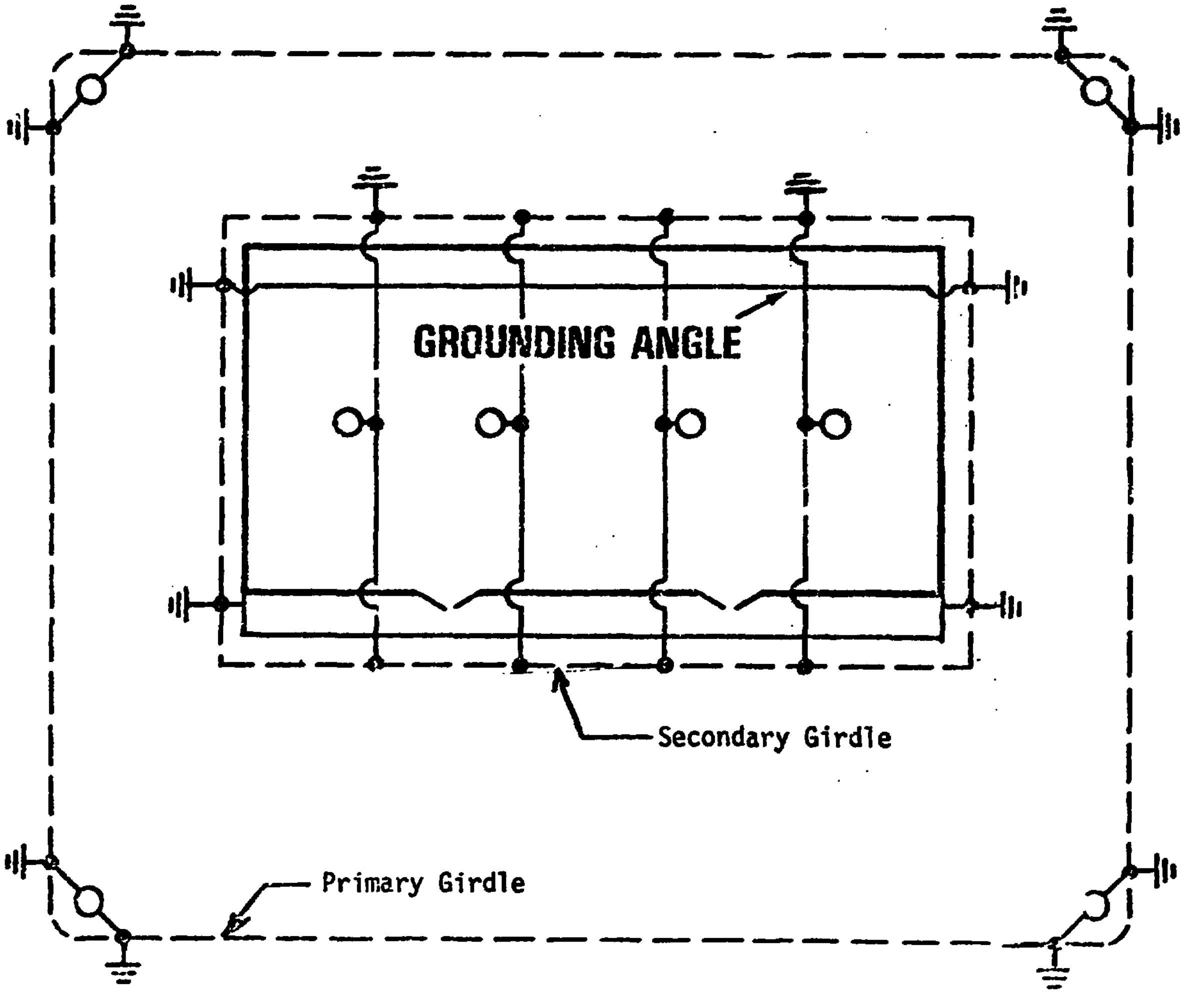
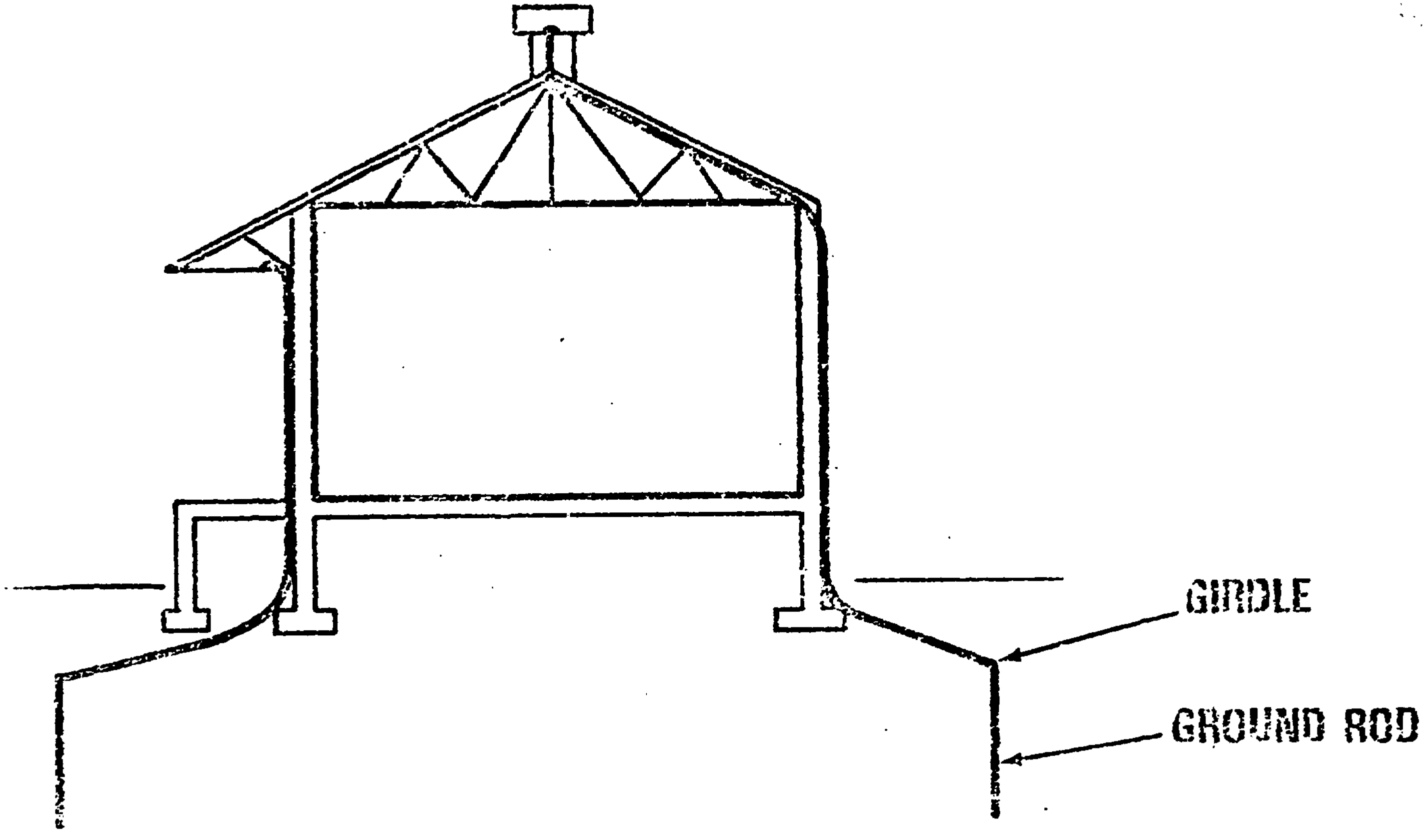


FIGURE 1 (b).

PRIMARY AND SECONDARY LIGHTNING PROTECTION SMOKELESS POWDER BUILDING (NO SCALE)



3.1.2.2 Secondary Protection Systems

Although not specifically required, the magazine was also provided with a secondary ground girdle. The secondary girdle is currently required to provide a common bond for all secondary grounding systems (i.e., static grounds, ordnance grounds, instrumentation grounds, etc.)[5]. Each steel truss was bonded to the secondary ground girdle. A No. 4 AWG solid copper cable bonded the trusses to a No. 2/0 stranded copper cable approximately 3 to 4 feet above grade on the rear and 1 to 2 feet above the loading dock on the front. The 2/0 cables were in turn bonded to the secondary girdle at the front and rear. Each copper ventilator was bonded to the nearest steel truss, which was in turn bonded to the secondary girdle at the front and rear of the structure. As mentioned above; doors, door frames, and all metal flashings were bonded as required.

Magazine 114 was also equipped with an ordnance ground system to ground the propellant containers inside the magazine. This grounding system consisted of a 1 1/4-inch wide copper mesh cable running along the rear of the magazine (3 feet from the rear wall), replacing the imbedded angle-iron originally provided, bonded at both ends to the secondary ground girdle. A total of 13 rows of copper-mesh cables were connected perpendicular to the ordnance ground bus.

3.2 Lightning Protection Requirements

3.2.1 Lake City AAP Requirements

The 19-Area magazines utilized integral lightning protection systems to protect the magazines from the effects of lightning. These systems were installed at approximately the time of construction and met the protection requirements in effect at the time [9] as evidenced by the receipt of Underwriters Laboratories Master Labels in 1947.

Hot air (steam) heating systems were installed in the magazines in 1953[2]. At this time the lightning protection system should have been upgraded to meet the requirements in effect at the time. No evidence is available to indicate this was considered although the only discrepancy noted by subsequent inspection was in the bonding and grounding of the steam pipes.

> **NOTE**: It could be interpreted that the protection system met a liberal interpretation of the requirements in effect during 1953. This will be discussed in greater detail in Section 3.4.

The magazines were reroofed in 1978 and the 18-inch air terminals were replaced with 24-inch terminals. No effort was made to upgrade the remainder of the system to the standards in effect at the time. A total upgrade was not required by the Army Safety Manual (AMCR 385-100).

3.2.2 NSWC Magazine 1L4 Requirements

The earliest copy of NAVSEA OP-5 available to the investigating team was BUORD OP-5 of 10 June 1944[10]. Although the structure was designed prior to this date (1940), it is thought that the earlier edition of the publication was similar. The 10 June 1944 edition of the publication was the first revision, superseding OP-5 dated 1 Oct 1920.

BUORD OP-5, June 1944 required that all magazines be equipped "with an efficient lightning protection system." Section 787 required that the primary lightning protection system, designed to intercept direct strikes, "consist of four or more masts each about twice the height of the building and placed a minimum of one-half the mast height from the corners of the building. A 2/0 copper-cable girdle connects the steel masts underground, laid not less than 18 inches below grade and completely surrounding the building."

BUORD OP-5 (1944), Section 790 requires that each steel column or truss be grounded at its lowest point. The ventilators, flashings, and frames of metal doors shall be bonded to the structural steel work, or connected to separate grounds. Number 6 AWG copper wire is required for all secondary ground connections. Bonding connections, from one grounded part to one to be grounded, shall not exceed 40 feet in length. Where the distance exceeds 40 feet, separate grounds shall be provided. Metal objects within buildings shall be grounded. Although a secondary ground girdle is not specifically required, Section 790 requires that all steel in the magazine be grounded and Section 791 discusses the effectiveness of interconnecting additional rods. Section 792 discusses the use of a 2/0 secondary girdle where driving ground rods is impractical.

Even though BUORD OP-5 (1944) does not address the number of ground rods, NFPA Code 78 (1937) [9] (the standard in effect at the time of both design and installation), Section 217 required a ground connection for each down conductor. Section 215 of NFPA 78 (1937) required 2 separate paths from each air terminal (mast) to ground. This was subsequently required by Navy Definitive Design Drawings (NAVFAC P-272) [16]. BUORD OP-5 (1944), Section 793 required that "the lightning protection systems and the static grounding system... be scrupulously examined semiannually, and shall be kept in efficient condition. Once each year each system shall be tested electrically and the results of these tests, together with the description of the defects noted and the repairs made, shall be submitted to the station safety engineer or the person designated as responsible for the efficient operation of the lightning protection system." The current revision of the document, NAVSEA OP-5, Volume 1, Fourth Revision, Change 14 [5], Chapter 4-9.2.4 and 4-9.2.5 requires visual inspections every 7 months and complete electrical tests every 14 months. Test results, any effect noticed, and repairs made shall be submitted to the person responsible for the efficient operation of the lightning protection systems and shall be entered in the activity records (NAVSEA OP-5, Volume 1, Fourth Revision, Change 14, 4-9.2.5). Chapter 4-9.2.4 requires that repairs of all discrepancies found during inspections be made immediately. Section 4.3 of this report discusses ground systems testing in greater detail.

3.3 Grounding

3.3.1 Lake City AAP Magazines

As mentioned in Section 3.1.1, the lightning protection grounding system was isolated from the "secondary" or static grounding system. However, in some cases (such as the heating system vent pipe) metallic conductors were bonded to the lightning protection system but grounded only through the static grounding system. As a result, a lightning strike that causes substantial current flow in the lightning protection system will create a corresponding voltage differential between the ground systems (since the grounding systems were not bonded at the ground level). As defined by Ohm's Law, the vent pipe will conduct a substantial current pulse into the structure because the static ground "looks like" a much lower impedance ground (the primary ground girdle will be saturated at this time). Due to the bonding/grounding technique used in the magazines, this surge current will likely flow through the "ordnance bus bar" to get into the secondary grounds.

The secondary, "static," grounding system consisted of a conductive deck and a 1-inch by 1/4-inch copper bus bar running along the interior wall. The steam pipes and heating system hardware were also grounded through the "static" ground system. Finally, the propellant containers were grounded through the static ground system due to the fact that they were sitting on a conductive deck.

3.3.2 NSWC Magazine 1L4

Magazine 1L4 was equipped with both primary and secondary ground girdles. The primary ground girdle interconnected the masts and provided paths to ground for lightning currents. The secondary ground girdle interconnected all the conductors located in or on the structure and provided a means by which the ordnance stored in the magazine could be grounded.

3.3.2.1 Primary Ground Girdle

The masts were interconnected by a 2/0 stranded copper cable. A total of eight 10-foot long ground rods were installed as part of this ground girdle; two for each mast. The girdle was buried a minimum of 2 feet below grade. It has not bonded to the secondary ground girdle.

3.3.2.2 Secondary Ground Girdle

A secondary ground girdle was installed to provide a common bond for all secondary grounding systems (static grounds, ordnance grounds, structural grounds, etc.). This girdle consisted of a 2/0 stranded copper cable buried approximately 2 feet below grade running 3 to 4 feet outside the perimeter of the structure. A total of 6 ground rods were connected to the secondary girdle as shown in Figure 1.

The copper ventilators and steel trusses were bonded to the secondary girdle by a No. 4 AWG solid copper cable running down the exterior of the structure in both front and rear (4 ea) to approximately 3 to 4 feet above grade. The No. 4 cable was then connected to a 2/0 stranded copper cable that provided the bond to the secondary girdle. Doors, door frames, and metal flashings were bonded to these conductors.

An ordnance grounding system had also been installed in the magazine. This consisted of a 1 1/4-inch wide tinned copper-mesh cable running along the rear of the magazine. A total of 13 rows of these cables were connected perpendicular to the bus. The ordnance in the magazine was grounded by sitting steel pallets (on which the propellant containers were stored) on this conductor. No "positive" attachment to the propellant containers was attempted. Any propellant containers that were sitting on wooden skids were not grounded.

3.3.3 Ground System Testing

3.3.3.1 Lake City AAP

Annual electrical tests were required for the grounding systems protecting the Lake City AAP magazines. These test results were not made available to the author but they were thought to meet the minimum ground resistance requirements of 10 ohms. However, the Lake City AAP engineering personnel conducting the tests were unaware that the magazines' lightning protection systems were equipped with counterpoises. The Army Board of Investigation Team concluded that the grounding systems had not been properly tested. Analysis of some of the magazines in the area confirmed that corrosion and broken connections existed in the area[1].

3.3.3.2 NSWC Magazine 1L4

Navy regulations have required both visual and electrical testing of lightning protection systems as early as 1944 [10]. Although current regulations (NAVSEA OP-5, Chapter 4-9.2.4) require 7 and 14 month test cycles vice the 6 and 12 month cycles of earlier days, both require that any damage noted during the tests be submitted to the person responsible for the efficient operation of the lightning protection systems and entered into the station's records. Current regulations require that repairs of all discrepancies be made immediately.

Table 1 provides ground system test results for the required ground system tests for the last 5 years. The grab bars identified in Table 1 are not required and had been removed at least 5 years prior to the incident. Conversely, Test Point 3, identified as missing for at minimum 5 years, was a necessary part of the secondary grounding system and should have been repaired immediately. One of the six total ground rods for the secondary girdle was located at the point that the missing bond tied into the secondary girdle.

Even though the test technique utilized by NSWC in conducting the required ground systems testing did not meet manufacturer's recommended procedure as is currently specified by NAVSEA OP-5, Chapter 4-9.2.5, it met the intent of NAVSEA OP-5. As can be seen in Table 1, the extensive interconnections of metallic objects with the secondary ground girdle can mask any deterioration of the grounding system when measured according to current requirements. For instance, after taking samples of the secondary bonding conductors for metallurgical evaluation (resulting in the disconnection of the bonds to the steel trusses) and conducting tests on the remaining girdle, it was found that one of the test points showed 120 ohms resistance when adjacent test points to which it was to have been interconnected read 1.7 to 1.8 ohms. The final entry in Table 1 forwards the values of the ground system test conducted after the incident. As mentioned earlier, excavation revealed that the secondary ground girdle was not continuous and the test point exhibiting the out-of-spec readings was found not to have been connected to the secondary ground girdle.

TABLE 1

GROUNDING SYSTEM TEST RECORDS FOR MAGAZINE 1L4

Test Point : Number	Description	Test Data (OHMS) 06/26/80	05/08/81	06/02/82	05/12/83	08/06/84	04/02/85	07/23/85
1		1.5	0.7	1.7	1.0	1.3	2.6	1.5
2		0.7	0.9	1.7	1.0	1.3	1.7	1.7
3	Building Ground	M I S S I N G						
4		2.2	0.9	1.6	1.0	1.3	1.8	1.7
5		2.2	0.8	1.6	1.0	2.0	1.8	1.7
6		3.8	1.2	1.7	1.0	1.3	1.8	1.7
7		4.0	0.8	4.0	1.0	1.3	1.6	2.0
8		1.6	0.9	2.8	1.0	1.8	1.8	1.8
9		0.5	0.8	2.0	0.8	1.8	1.6	1.8
10		0.7	0.8	1.6	1.0	1.5	1.8	1.7
11	Static Ground	M I S S I N G						
12		2.2	0.9	1.6	1.2	1.3	1.8	1.7
13		2.2	0.9	1.7	1.0	1.5	1.7	1.7
14	Static Handle	M I S S I N G						
15		0.6	0.7	1.6	1.0	2.0	5.0	120
16		2.0	1.2	4.0	1.0	1.5	3.8	1.8
17	Static Handle	M I S S I N G						
18		0.6	1.3	1.6	1.0	1.5	1.8	1.7
19		3.0	1.2	1.6	1.0	1.5	2.6	1.7
20		2.0	0.9	1.6	1.0	1.5	1.7	1.7
21		0.5	1.4	1.8	1.0	1.4	1.8	1.5

3.4 Lightning Protection System Analysis

3.4.1 Lake City AAP Analysis

The "19 Area" magazines were inspected on 7-8 March 1984 to provide comments to Army and Remington personnel (contractor at the time of the incidents) on what specific modifications to the systems would be necessary to bring the grounding and lightning protection systems up to current standards. Minor differences existed among the magazines inspected but generally the systems contained an excessive number of bends in the down conductors, the steam pipes and vent pipe were not properly grounded and the lightning protection ground girdle was not interconnected with the static grounds.

The most widespread discrepancy identified in the "19 Area" magazines was the coursing of the down conductors. NFPA 78-1983 [7], Sections 3-14 and 3-15 require that conductors maintain a horizontal or downward course, free from pockets. No bend of a conductor shall form an included angle of less than 90 degrees nor have a bend radius less than 8-inches. A large number of the down conductors which were looped around the eaves violated both requirements.

The steam pipes were in most cases bonded to the lightning protection system but in some cases were not grounded at that point. They must be grounded to the lightning protection system at that point. In addition, some of the cabling used to bond the steam pipes was too long. They should be much more direct. If not properly grounded to the lightning protection system's ground girdle with as short and direct a cable as practical, the currents induced on the steam pipes as a result of a "far field" lightning or due to a direct strike to the protection system (because of the bond) may instead flow through the static grounding system (especially since the grounding systems are isolated) just as in the case of the vent pipe.

The vent pipe coming from the equipment room penetrates the roof level and is therefore bonded to the roof conductors of the lightning protection system. However, the pipe is never grounded with the lightning protection system. Instead, it runs back through the equipment room, through the static bus bar and is finally grounded through the static ground system. This is the most serious discrepancy noted during the inspection. Should the magazine be struck by lightning some portion of the lightning current would flow through the equipment room and onto the static bus bar. Since the propellant drums in some magazines were stacked within inches of this bus bar, a potential for sideflash exists. This sideflash could be of sufficient energy to cause arcing inside the drum, resulting in a deflagration. Tests conducted on LeverPak drums by NSWC also indicate that this internal arcing could occur even without the sideflash. These tests are discussed in Section 5. The vent pipe must be grounded to the lightning protection system's grounding system at its lowest external point.

Upon inspection of the lightning protection grounding system much corrosion was noted at joints, especially those underground. The integrity of the primary girdle should be confirmed and the static grounds as well as railroad tracks should be bonded to this girdle.

There were other minor discrepancies noted. The majority of these can be summarized by bond wires that had come apart and had not been replaced. In general, the systems were not being maintained properly. This was thought to be in part due to improper training of the personnel conducting the inspections. Those talked to during the inspection indicated they were not sure what to look for when inspecting an integral lightning protection system. We recommended that, at minimum, those tasked to inspect the lightning protection systems be trained in the inspection of integral protection systems.

Finally, the inspection and background discussion revealed that there was an inadequate amount of coordination with the person responsible for the efficient operation of the lightning protection system (LPS) when modifications were made to the structure. This is evidenced by the fact that the LPS was not properly bonded to the hot air heating system when installed. Additionally, the system was not upgraded to remedy this condition when the magazines were reroofed even though the air terminal heights were modified (which was not as serious a problem).

3.4.2 NSWC Magazine 114 Analysis

As previously discussed, the mast-type lightning protection system installed to protect the magazine was designed in 1940 and installed in 1941. Mast heights were designed such that the tip of each mast was 59 feet above deck level. This is exactly twice the height of the structure (28 feet). The masts were spaced 32 feet from the corner of the structure. Today's lightning protection standards require that the masts be of adequate height to provide a zone-of-protection based on a striking distance of 100 feet. The protection system in use at the time of the incident would not meet today's zone-of-protection requirements.

The masts were properly interconnected via a 2/0 copper ground girdle. However, when excavating the ground girdle to ensure there was no corrosion and that the system had been properly installed, it was found that approximately 20 feet of the girdle was missing. Visual inspection of the ends of the existing cable revealed that the conductor had been cut prior to the time of excavation. The secondary ground girdle was missing approximately a 25 foot section in this same area. It is assumed that these girdles were probably damaged when the railroad tracks, installed at the time of construction were removed.

Current testing requirements are not designed to detect missing sections of counterpoises. Any damage of this sort can only be detected visually and must be repaired prior to the completion of any construction project associated with a magazine or explosives-operating building.

The structural steel in the roof was well interconnected. The roof was designed to be bonded to the secondary ground girdleat eight places, however two of these bonds were missing; one on the front-left (undetected) and one on the rear-right (detected). The propellant containers were located on metal pallets and their tops were approximately 4 to 5 feet above deck level, depending on the type of container. The containers were grounded through high inductance contact associated with the containers sitting on pallets which in turn were sitting on one of the 13 rows of 1 1/4-inch wide copper mesh cable. These cables extended, parallel, 31 feet toward the front of the magazine and were bonded to the ordnance ground running along the rear of the magazine. The ordnance grounding system had been recently replaced and appeared to be in good condition in those places that were not damaged by the deflagration. However, upon investigation of the ordnance grounding system it was found that the "West" bond to the secondary ground girdle was broken and making minimum contact at the connector. However, Navy regulations do not require that the propellant containers be grounded in a magazine of this type.

4. IGNITION SOURCES

4.1 Lake City AAP Magazine 19L

The Army Board of Investigation Report on the Deflagration of Magazine 19L examined five primary sources of ignition [2]. These were:

(a) Sabotage or Human Error
(b) Electrical
(c) Mechanical
(d) Chemical
(e) Atmospheric

Each was investigated in detail and based on combined eyewitness testimony, physical evidence, interviews, records and reports, the Board of Investigation concluded that a lightning strike (possibly a direct strike) was the most probable cause of the fire on 22 February 1979.

4.2 Lake City AAP Magazine 198

The investigation of the deflagration of Magazine 198 examined the same five ignition sources as considered in the investigation of the deflagration of Magazine 19L because of the similarities. In this case, lightning activity was occurring immediately before and after the fire even though reports differ on the presence at the time of the fire. Operations had been suspended because of lightning activity up until approximately 15 minutes prior to the deflagration.

4.3 NSWC Magazine 1L4

Magazine 1L4 was not equipped with any type of electrical service, fire alarm system nor plumbing, etc. NOS/Indian Head [16] tested samples of propellant lots stored in the magazine and found each to be stable. The structural steel in the roof trusses were found to be magnetized after the event; unlike similar structures checked at NOS/Indian Head. The most probable cause of this deflagration was identified as atmospheric.

4.4 LeverPak Propellant Containers

Each of the three magazines discussed in this report was storing propellant in LeverPak fiberboard drums. The LeverPak drums consist of nine layers of 1-ply Kraft Linerboard (45 lbs/1000 sq ft) and one layer of aluminum foil vapor barrier. The aluminum barrier consists of 0.0005 foil laminated with resin adhesive between two plies of 23 lbs/1000 SQ FT Kraft Linerboard. The aluminum vapor barrier is located 1-ply outside of the inner wall of the container. An aluminum foil liner disc is required on the inside layer of the bottom of the drum. This liner disc must be connected electrically to the bottom steel chime. A 1-inch wide, 5-mil thick strip aluminum foil tape is required in the

"Navy" drums to bond the top and bottom steel chimes. The LeverPak drums stored in the Lake City AAP magazines did not have this interior foil bond. Navy requirements specify that the drums not exceed 5-ohms resistance between the top and bottom chimes at the time of delivery. However, those drums taken from NSWC earth-covered magazines exhibited much higher resistances between the top and bottom chimes (probably due to oxidation of the aluminum surfaces).

Under current impulse conditions the interior aluminum foil strip would probably vaporize and internal arcing is also likely to occur. Tests run at NSWC/Dahlgren, Virginia repeatedly vaporized this interior foil strip using only 50 amperes ac (60 Hz) current [12].

Upon examination of the construction drawings and making some DC-resistance measurements, NSWC Code H12 felt that the containers may also be susceptible to internal arcing due to rapidly changing (high di/dt) currents as well as the high peak currents that would vaporize the internal foil strip. As a result, electrostatic discharge (ESD) tests were conducted on the drums. The results of these tests are forwarded in Section 5.

5. ELECTROSTATIC DISCHARGE TESTING OF LEVERPAK DRUMS

In an effort to investigate the significance of the presence of LeverPak drums in both the February 1979 and September 1984 Lake City AAP incidents as well as the 12 July 1985 Dahlgren incident, NSWC Code H12 conducted both direct electrostatic discharge (ESD) and nearby ESD tests on a sample of 16 of the LeverPak drums that were in use in NSWC/DL earth-covered magazines. These drums were provided by the NSWC Ordnance Officer (Code G01/CDR T. W. Moore) for these follow-up tests as proposed in NAVSWC Message 161900Z September 1985 [17].

Lake City AAP also provided NSWC Code H12 with a sample of the type of LeverPak drums that in both Magazines 19L and 19S at the time of their respective deflagrations. These drums are similar to the drums stored in the NSWC magazine with the exception that the "Army" drums have no aluminum foil bottom nor aluminum foil strip bonding the top and bottom chimes. Additionally, the Army containers sampled were in much better condition than the drums pulled from NSWC magazines. Based on resistance measurements made with a Beckman HD-100 Digital Multimeter (DMM), the Lake City AAP drums exhibited less evidence of internal oxidation around the aluminum crimp points than the older "Navy" drums tested.

In the remainder of this report the term "Navy" drum will refer to the LeverPak drums which include both the foil bottom (internal) and the internal foil strip bonding the top and bottom chimes. Correspondingly, the term "Army" drums will refer to the LeverPak drums furnished by Lake City AAP which have the same aluminum foil vapor barrier buried in the wall but do not have the internal foil bottom nor the internal strip bonding the top and bottom chimes.

5.1 Test Configuration

The NSWC Electrostatic Discharge (ESD) Test Laboratory (Building 276) was used to subject the LeverPak drums to both direct and radiated electromagnetic impulses (EMP) generated by a high-voltage discharge from a Hipotronics Model IG400-4 Impulse Generator. The Impulse Generator consists of a bank of 4 x 2000 picofarad capacitors charged to 100,000 volts DC (100 kV) while interconnected in parallel and then switched to a series combination immediately prior to their discharge (as per a Marx Generator) resulting in an impulse voltage of up to 400 kV. The output of the Impulse Generator is than connected across a 2000 picofarad capacitive divider for waveshaping and output voltage monitoring. The load is then connected across the capacitive divider.

5.2 ESD Tests on "Navy" Drums

A total of 16 "Navy-type" LeverPak drums were tested in a variety of configurations. The drums were subjected to both direct and nearby (indirect) ESD impulses. In each case the DC-resistance measured between the top locking ring and the bottom chime (using a Beckman HD100 Digital Multi meter (DMM)) decreased to a short-circuit value after a direct discharge as shown in Table 2. This change in resistance suggested that sparking was present which "w elded" a small contact area between the foil strip or vapor barrier and the top and bottom chimes.

Another group of "Navy" drums were subjected to radiated EMP tests. The Impulse Generator was discharged through a 100-ohm resistor terminated through approximately 4 feet of 1 1/4-inch wide copper mesh vertical conductor. In most cases the drums were isolated from the discharge circuit by one to two inches with the largest spacing being approximately 5 inches. In all cases the DC resistance decreased to a short circuit value after being subjected to impulse voltages ranging in value between 360 and 400 kV.

In one case a drum was isolated from the vertical conductor by a distance of 12.5 feet and "shielded" by a second drum only 1-inch away. The DC resistance of the drum decreased from approximately 750 kiloohms to 44 ohms. After a second discharge, also "shielded" by a second drum, the resistance of the drum decreased from the 44 ohms to that of a short circuit. The EMP produced by two separate discharges was adequate to short the drum even though it was never closer than 12.5 feet to the impulse source.

In another sequence of tests, a total of three drums were isolated from the ground plane by 1-inch by 1-inch wooden blocks and then subjected to an impulse. The spacing between the drums and the vertical channel was 2-inches in all three cases. The purpose of this sequence of tests was to determine whether the arcing (or fuzing) was less likely to occur if the drums were not grounded. In two of the three tests, the impulses resulted in the shorting of the top and bottom chimes.

A final sequence of tests was conducted on some of the "Navy" drums after removal of the interior foil strip. In each case the drums were shorted even though the internal bonding strip had been removed. Such tests provided a possible link between the Dahlgren and Lake City incidents and justified the decision to do a series of tests on the "Army" type LeverPak drums. Test results for the radiated discharge tests are forwarded in Table 3.

5.3 ESD TESTS ON "ARMY" DRUMS

Lake City Army Ammunition Plant shipped a total of twelve of the "Army" LeverPak drums to the NSWC/Dahlgren Laboratory for electrostatic discharge (ESD) testing. Six of the drums were of similar size as the drums in the Dahlgren magazine (27-inches tall by 16-inches in diameter). The other six were of similar design to the other "Army" units, but smaller in size (23-inches tall by 14.5-inches diameter).

The "Army" drums were in much better condition than the "Navy" drums tested. The drums were electrically "new" although they had been used and were scheduled for disposal. No evidence of corrosion or oxidation could be detected in the "Army" drums. Because of this, the DC resistance of the "Army" drums was generally much less than that of the "Navy" drums even though the "Navy" drums had an internal aluminum strip bonding the top and bottom chimes (which the "Army" drums did not have).

The "Army" drums were all subjected to the radiated ESD tests. All drums were placed on the ground plane, spaced 1-inch from the vertical conductor.

Table 4 forwards the results of these tests conducted on the "Army" drums on 27 and 29 November 1985. Drum size "A" refers to the 27-inch tall drum with drum size "B" referring to the 23-inch tall drums. The pre-resistance (R_{pre}) values reflect the DC resistance measured between the locking ring and the bottom chime after the drum has been installed in the test cell, immediately prior to the impulse. The post-resistance (R_{post}) values reflect the DC resistance measured at the same points as before the impulse; taken prior to removal of the drum from the test cell. These values reflect the resistance values after compensation for any offset of the Beckman HD100 DMM used to make such measurements.

The first series of tests (Tests 1-12) were conducted on the drums as received. As shown in the table, each drum was shorted after being subjected to a single impulse whose voltage peak ranged in value between 350 and 400kV.

In an effort to determine the extent of internal fuzing, shock tests were conducted on those drums previously tested to see if an increase in resisitance could be achieved. The theory behind such tests would be to confirm that the shorting of the drums was due to internal arcing that fuzed the vapor barrier and chimes together at a small surface area. If so, one should be able to break this contact point with a proper amount of physical shock. The drums were taken out onto a concreate dock and "dropped" along the top and bottom chimes. In all cases the drums increased in resistance after being subjected to physical shock; and in all but one case the resistance was greater than or equal to its original resistance value.

TABLE 2

DIRECT DISCHARGE TESTS ON "NAVY" DRUMS

DRUM #	R_{PRE}(ohms)	V_{POST}(ohms)	$V_{DISCHARGE}$
1	10.5	0.0	360kV & 400kV
2	20.2	0.0	320kV
3	0.3	0.0	200kV

TABLE 3

RADIATED DISCHARGE TESTS ON "NAVY" DRUMS

(100 ohm Load Resistance with 1-inch Vertical Strap)

TEST #	DRUM #	GAP	R_{PRE}(ohms)	R_{POST}(ohms)	$V_{DISCHARGE}$	COMMENTS
1	3	1"	0.8	0.1	200kV & 200kV	
2	4	1"	2.2	0.2	384kV & 200kV	
3	13	1"	202	0.0	400kV	
4	11	1"	256K	0.1	360kV	
5	6	1"	0.2	0.0	400kV	
6	6	1"	3.2M	0.1	384kV	Removed internal strip
7	6	1"	>20M	0.2	400kV	"Banged Out"
7	15	12.5'	10M	10	400kV	
8	3	2"	44K	26K	384kV	Internal strip removed
8	15	12.5'	8.4	0.1	384kV	
9	7	1.5"	5-6M	>20M	376kV	Isolated by 1" wood blocks
10	7	1.5"	>20M	0.0	384kV	On gnd plane
11	5	1"-2"	1.0K	0.2	400kV	Isolated by 1" wood
11	7	2"	200K	0.1	400kV	*Internal strip removed
12	5	5"	17M	0.2	400kV	Isolated
12	7	5"	440K	0.1	400kV	Internal strip removed

*R_{DRUM} WAS SHORTED EVEN AFTER STRIP BROKEN. SHOCKED TO GET RESISTANCE > 0.

TABLE 4. SUMMARY OF ELECTROSTATIC DISCHARGE TESTS CONDUCTED ON DRUMS FURNISHED BY LAKE CITY AAP

TEST NO.	DRUM NO.	Size[a]	R_{PRE}[c]	R_{POST}[c]	$V_{DISCHARGE}$
1	A1	A	0.4	0.0	400kV
2	A2	A	0.3	0.0	376kV
3	A3	A	9.2	0.0	368kV
4	A4	A	2.7	0.0	352kV
5	A5	A	0.3	0.0	400kV
6	A6	A	0.2	0.0	400kV
7	A7	B	0.4	0.0	392kV
8	A8	B	0.6	0.0	368kV
9	A9	B	8.8	0.0	384kV
10	A10	B	258	0.0	352kV
11	A11	B	0.6	0.0	368kV
12	A12	B	0.5	0.0	360kV
13	A1	A	0.5	0.0	384kV
14	A2	A	>20M	>20M[d]	400kV
15	A2	A	>20M	0.0	360kV
16	A3	A	9.0	0.0	400kV
17	A4	A	54	0.0	400kV
18	A5	A	22.8	0.0	400kV
19	A6	A	1.1	0.0	400kV
20	A7	B	0.7	0.0	400kV

TABLE 4. (continued) SUMMARY OF ELECTROSTATIC DISCHARGE TESTS CONDUCTED ON DRUMS FURNISHED BY LAKE CITY AAP

TEST NO.	DRUM NO.	Size[a]	R_{PRE}[b]	R_{POST}[c]	$V_{DISCHARGE}$
21	A8	B	0.6	0.0	400kV
22	A9	B	1.7	0.0	400kV
23	A10	B	2.3	0.0	400kV
24	A11	B	0.8	0.0	400kV
25	A12	B	2.0	0.0	400kV

a. Size A = 27 inches tall x 16 inches dia, Size B = 23 inches tall x 14.5 inches dia.

b. R_{pre} are resistance values recorded after the drum was installed in the test cell just before the discharge.

c. R_{post} are resistance values recorded after the discharge prior to removal of drum from test cell. All values have been compensated for any zero offset of digital multi-meter.

d. In conditioning of drums for second test the drums were dropped on the respective chimes. The locking ring on the top of the drum was not removed.

Tests No. 13 through 25 forward the results of this second series of tests. In all but one case during this series of tests, the drums were again shorted. Prior to Test No. 14, shorted drum (A2) was taken out ot the concrete dock and dropped on the top and bottom chimes. As in each case during the second series of tests, the drum was shocked with its top and locking ring attached. The resistance of drum A2 was measured and found to exceed the limits of the multimeter being used (20 megohms). The drum was brought into the test cell, the resistance measured and found again to exceed 20 megohms. After an impulse voltage of 400kV peak (1-inch away) the drum still exhibited a resistance of greater than 20 megohms. Between Test No. 14 and 15 the top of the drum was removed and resealed. The locking ring was reinstalled, the resistance again measured and found to be greater than 20 megohms. Test No. 15 was conducted; subjecting the same drum to a 400kV peak impulse. After this second impulse, Drum A2 was found to be shorted.

5.4 SUMMARY OF ESD TEST RESULTS

In summary, all drums tested in both "Army" and "Navy" configurations were decreased in resistance after being subjected to two discharges from the Hipotronics IG400-4 Impulse Generator. In most cases this shorting occurred after only a single impulse. It is postulated that the decrease in resistance between the top and bottom of the drums was caused by internal arcing between the top chime and the vapor barrier buried in the wall of the drum and between the vapor barrier and the bottom chime. This arcing is significant because it is most likely to occur in the creases along the top and bottom chimes where explosives dusts or volatiles (ether, etc.) are more likely to be present. Hudson [18] confirmed that explosives concentrations can be present in the LeverPak drums. An Army study conducted for Indiana Army Ammunition Plant identified that as little as 0.13 milliJoules is required to initiate vapor/air mixtures that could be present in the LeverPak drums [19]. Both sources identified that aging of the propellant and subjecting the propellant to temperatures exceeding 100°F were factors that would increase the concentration of volatiles in the container. In the Dahlgren incident there were some LeverPak drums that may not have been opened for up to 10 years. During the survey of the "19 Area" magazines the author noted temperatures exceeding 100°F in a few of the magazines. The Army Board of Investigation Report on the 13 September 1984 incident reported a temperature of 105°F in Magazine 19S the evening of the incident [1]. NSWC recommended by message on 16 September 1985 that LeverPak containers be removed from all Navy above-ground magazines [17]. Test results support this recommendation. It is even more critical that the drums be removed from those above-ground magazines that have no lightning protection or have an integral lightning protection system.

6. Summary

6.1 Conclusion

After reviewing Army Board of Investigation reports, inspecting the lightning protection systems, and conducting high voltage ESD tests on containers, we conclude that the 13 September 1984 and most likely the 22 February 1979 magazine deflagrations were lightning-related. Lightning currents were induced onto the integral protection system's grounding system either by a direct strike or by the radiated electromagnetic pulse produced by nearby lightning. The current impulse would be divided between the primary grounding system and the static grounding system because of the bond to the vent pipe (which was not grounded with the lightning protection system). This current impulse would flow through the equipment room and onto the static bus bar where it would find "ground" (0-volt potential). NSWC tests have confirmed that when impulsed the LeverPak drums would decrease in resistance, implying internal sparking. With temperatures exceeding 100°F in the magazine, it is concluded that an explosive vapor would be present in the drums[18]. The sparking could easily be of sufficient energy to cause ignition of the internal gases. The resulting deflagration could then occur.

Adequate data also exists to conclude that the 12 July 1985 deflagration of NSWC/Dahlgren Magazine 1L4 was caused by a lightning discharge. A low-energy cloud-to-ground discharge probably struck the second ventilator from the East wall. The resulting return stroke was significant to produce a sideflash to a LeverPak propellant container or produce magnetic fields of significant magnitude to induce arcing inside a LeverPak container.

Sparking inside the LeverPak container probably ignited ether gas or propellant dusts in one of the drums. A resulting fire could cause a major deflagration.

In none of the three incidents did an eyewitness report a direct strike to the structure prior to its deflagration. Sparking inside LeverPak containers would not require a direct strike based on the ESD test data forwarded in Tables 2-4.

The integral lightning protection systems for the "19 Area" magazines at Lake city AAP met the requirements at the time of installation (based on the UL Master Label). However, when the hot air (steam) heating system was installed the steam lines and vent pipe were bonded to the lightning protection system but not properly grounded. Both the steam lines and vent pipe must be bonded to the lightning protection system ground girdle as identified in Section 3. Additionally, the railroad tracks must be grounded as per AMCR 385-100[8], Chapter 8-17 and bonded to the lightning protection ground girdle.

The down conductors contained an excessive number of bends and in many cases had pockets as per NFPA 78-1983 Section 3-14 and bends that contained bend radii much less than the 8-inch radius specified. These discrepancies should be eliminated immediately.

The primary (lightning protection) ground girdle should be verified to be free of corrosion. A secondary ground girdle should also be added to interconnect the structural grounds and static grounding system. These two girdles must be tied together when installed.

The inspection also revealed that those people tasked to inspect the lightning protection systems were not properly trained and were not sure what to look for when conducting the inspection. These personnel must receive proper training in lightning protection prior to their conducting any inspections in order to ensure the systems are properly maintained. This is especially critical when integral protection systems are used.

Neither the testing techniques recommended by NAVSEA OP-5 [5] nor AMCR 385-100[8] was found not to be adequate to detect broken ground girdles or broken cables when the break is not visual (such as underground). The multiple number of bonds to the girdle provide many parallel paths to ground and can mask any open circuits. However, NSWC Magazine 1L4 had one bond from the roof to the secondary girdle on the rear that had been missing for a long period. The conductor was identified as a test point on the ground system test record. The records show the conductor had been missing for 5 years and it had not been repaired; which is a violation of NAVSEA OP-5, Chapter 4-9.2.5. The West bond between the ordnance grounding system and the secondary girdle was broken at the interconnection between the No. 4 AWG solid cable coming from the interior of the magazine to the 2/0 stranded copper cable that entered the ground and made contact with the secondary girdle. The ordnance grounding system had been recently replaced and had not been tested since completion of the task.

In summary, it must be emphasized that the required 7 month visual tests on lightning protection systems are as important as electrical tests required every 14 months. It is also important that all bonds accessible be physically shaken to ensure they have not been broken. The test results must be forwarded to the person responsible for the efficient operation of the lightning protection systems so repairs can be made. These repairs must be made in a "timely" manner.

Finally, it was found during this investigation that, even though not required, the majority of Navy facilities ground propellant containers in magazines with ordnance grounding systems which are designed to requirements based on production facilities. In magazines with no electrical service it is recommended that multiple bonds to the secondary girdle be made vice the single-point grounding system specified by NAVSEA OP-5 for production facilities. It is recommended that NAVSEA and the Army Materiel Command review current magazine grounding requirements and clarify to ordnance facilities whether containers in magazines should be grounded and, if so, how.

6.2 Recommendations

In order to adequately protect structures housing explosives from the effects of lightning, the containers in which the explosives materials are stored must be considered. Some designs of propellant storage containers are more susceptible to radiated magnetic fields than others.

Based on the results of ESD tests conducted on LeverPak propellant containers, NSWC recommends that LeverPak bulk propellant containers be gradually purged from the DOD inventory. In the interim, we recommend that these containers be stored only in earth-covered, Class I magazines[5].

It is recommended that the Lake City AAP "19 Area" magazines be protected with a mast or overhead-wire lightning protection system. By isolating the protection system from the structure, the effect of the radiated EMP from the strike is minimized. Additionally, the inspection of such a system is simpler and the amount of maintenance is generally reduced.

A plant/base should identify a person as responsible for the efficient operation of all lightning protection systems. This person must be trained in the protection of structures housing explosives. Having received proper training, this person should review all modifications to/around a structure with a lightning protection system to determine whether the modification will affect the lightning protection of the structure and, if so, must inspect the site during and after the modification to ensure the protection system was not compromised.

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Prepositioning and Rapid Deployment New Challanges in Ammunition Storage

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Prepositioning of ammunition in OCONUS locations and storage of ammunition for rapid deployment represents a significant departure from traditional storage configurations within the continental limits of the United States and overseas as well.

Traditional storage facilities and procedures are contrasted with recent requirements resulting from prepositioning and rapid deployment.

Good Afternoon. I am Tom Lighthiser, a Logistics Management Specialist employed at the U.S. Army Defense Ammunition Center and School, Savanna, Illinois. For the next 20 minutes I will briefly describe relatively recent changes that have occurred in ammunition storage in the Army throughout the world.

No country in the world, the United States included, can possibly produce, ship, and store <u>all</u> material required to support a conflict at <u>all</u> potential locations. Although conflicts have prompted us to position significant force structure in Europe and Korea, the success of the United States in the future may well rest upon the prepositioning of materiel and the ability to rapidly deploy our fighting forces.

In order to establish a baseline understanding of the more traditional ammunition storage, I will first describe and depict wholesale and retail ammunition storage in the United States followed by a brief discussion of storage overseas. I will then briefly discuss prepositioning of ammunition and storage for rapid deployment.

Army ammunition is stored within the continental limits of the United States at 12 DESCOM depots and depot activities, and numerous AMCCOM plants and arsenals at which the ammunition/explosives are produced. We refer to this as wholesale storage, as the ammunition accountability is maintained by the respective NICP, AMCCOM, OR MICOM, or remains in the industrial base. There are exceptions to certain depots storing retail ammunition designated for rapid deployment. The ammunition stored in depots and plants is characterized by large lot sizes and standard storage facilities are used. Within the depot complex, we have in excess of 10,300 storage facilities while the ammunition plants have approximately the same number. Over 2,000,000 S/T of ammunition is presently stored in the wholesale storage base. The slides that follow depict typical depot/plant ammunition facilities and storage:

Stradley Magazine
Above-ground Magazine
Navy 5" Gun Ammunition In An Army Igloo Magazine
AF MK84 2000# Bombs In An Army Stradley Magazine
Palletized Boxed Ammunition In An Army Igloo Magazine
155MM Projectiles in Navy-Type Earth-covered Magazine

Additional ammunition is stored at the posts, camps, and stations subordinate to FORSCOM and TRADOC where it is used for training purposes, and to a limited extent, consists of storage of unit basic load (UBL) ammunition, some of which is rigged for aerial delivery and/or airlift. This ammunition is referred to as retail in that the unit having custody of the ammunition is also accountable for it. As you might expect, this ammunition represents much smaller quantities, and generally consists of a greater mix. The training ammunition is tailored to the specific training requirements while the UBL is based upon specific weapons, densities, rates, mission, etc. Ammunition storage facilities in the posts, camps, and stations vary in size and construction from wooden and metal magazines built prior to World War II to the latest magazine design. The ammunition stored is generally limited to several hundred short tons representing the annual training requirement and UBL. The following slides depict typical facilities and storage in the posts, camps, and stations:

Non-Standard Earth-covered Magazine
Non-Standard Earth-covered Magazine
Underground Magazine Previously Used For Special Weapons
Boxed Ammunition In Wooden Magazine
Small Lots/Light Boxes
Unit Basic Load

The U.S. Army stores significant quantities of ammunition outside the continental limits in depots in Germany, England, Italy, Belgium, Japan, and Korea. Although not wholesale stock, per se, the Army has wholesale-like ammunition identical to the stocks stored in the CONUS depots and plants, and it is characterized by large quantities and large lots. Unlike the uniformity in storage structures that exists within the United States, storage facilities in overseas areas were often built by the host country according to their specifications and are as varied as there are countries involved. The variety of storage structures utilized in overseas depots is shown in the following slides:

Type 16 Magazine - Germany
Aerial View Of CADA And U.S. Constructed AGM - United Kingdom
AGM CADA - United Kingdom
155MM Projectile Storage In British Box Magazine
AGM - Italy
U.S. Stradley Magazine - Italy
Prop Charges - Italy
Boxed Ammunition In German Stradley - Belgium

Hillside - Korea
ECM - Korea
1950 Vintage Quonset Hut - Korea, most of which are rapidly disappearing
New Stradley-Type Magazine - Korea
Cave - Japan
Cave - Japan

The ammunition overseas comparable to the retail level stock within the CONUS at the posts, camps, and stations is stored in Ammunition Supply Points (ASPs), Prestock Points (PSPs), Reserve Ammunition Supply Points (RASPs), Basic Load Storage Areas (BLSAs), Ammunition Holding Areas (AHAs), Quick Reaction Sites (QRSs), Forward Storage Sites (FSTs), etc., located at the various overseas locations. This ammunition is very similar to the retail stock within the CONUS except that much of it is UBL that is positioned at, or in close proximity to, its potential point of use along the border in eastern Germany or along the DMZ in South Korea.

As indicated earlier, a great variety of structures exist in the overseas theaters. In recent years, the United States has constructed numerous standard magazines overseas and has even developed specially designed facilities to permit rapid re-supply in a forward area. The QRSs in Germany are representative of specially designed structures compatible with specific weapons systems. A self-propelled M109 155mm Howitzer is shown returning to a QRS. The QRS consists of earth-covered magazines having a common headwall and doors on both ends, whereas the smaller shed-type buildings were designed to store specific unit loads of tank and artillery ammunition. The dock heights are compatible with specific tracked vehicles and/or tanks.

The next series of slides will depict storage conditions for UBLs in Korea and Germany. The UBL storage depicted are the same types of ammunition and configurations that you will see later in rapid deployment UBL stocks stored at various installations, both posts, camps, stations, and depots within the continental limits. The primary difference, of course, lies in the geography as the UBL ammunition overeseas is positioned near its anticipated point of use, whereas the UBL in the CONUS is configured for rapid movement to any location in the world where it may be required.

The slides that follow depict typical AHAs in Korea:

Tank Park
M113 APC AHA
Trailer Mounted UBL
Engineer Battalion UBL Trailer Mounted
155MM Howitzer AHA
155MM Howitzer AHA
ADA UBL AHA
Aerial View AHA
Aerial View AHA

The next series of slides depict tank parks and BLSAs in Germany:

Tank Park
Artillery BLSA UBL
Artillery Trailer Mounted
Artillery BLSA
Artillery BLSA
Bulk Storage
Open Storage UBL In Winter

The Explosive Safety Standards that govern ammunition/explosive storage throughout the Army evolve from the DOD 6055.9 STD as shown in the slide. The DOD standard is prescribed within the Army by AR 385-64 which is further implemented by TM 9-1300-206, and AMC-R 385-100. In some areas, additional criteria is used when required by the host nation, e.g., the NATO standards are used in Germany. In recent years, the storage requirements at the retail level, particularly as they apply to UBL storage, have been changed to reflect criteria that is more permissive when operational considerations violate the prescribed standard.

The pre-positioning of United States equipment in Europe began in the 60s in response to United States and European concerns that forces in the theater were inadequate to meet the WARSAW Pack Threat. The Army has met the threat with heavy equipment for four divisions and supporting units and is currently pre-positioning more materiel in the European area. The levels of pre-positioned munitions, however, continue to fall short of objectives. The United States' goal is to possess sufficient war reserve stocks to sustain wartime activity until industrial production can provide the required support. The long-range goal is to correct the NATO-WARSAW Pack sustainability imbalance by the 1990s.

The Soviet invasion of Afghanistan and the revolutionary Iranian government's seizure of American hostages in late 1979 called attention to the lack of United States conventional military capability in the Indian Ocean area. This situation contrasted with Europe in that there was no mainland base to pre-position materiel.

The Island of Diego Garcia offered a secure base of operations, but fell short of needed storage area to stockpile materiel. Accordingly, the following year the Department of Defense established a pre-positioning force of merchant-type ships to carry equipment, weapons, and provisions to support a marine-amphibious brigade. The troops themselves would be flown out to the area and "married" with the equipment in a friendly port area.

Initially, seven ships (contract-manned and under charter to the Military Sealift Command (MSC)), comprised what was to be called Near Term Pre-Positioning Force (NTPF) and were located off the Island of Diego Garcia in July 1980. The force consisted of three RO/RO vehicle ships, two commercial breakbulk cargo ships, and two commercial medium-sized tankers. NTPF was established as a quick and efficient means of achieving dedicated sealift in the Indian Ocean, a region without mainland staging site for military units. Similar to the European pre-positioning plan, the Near Term Pre-Positioning

Ships Program (PREPO) was designed to augment our reinforcement in the Indian Ocean regions while minimizing the impact upon our strategic mobility capability.

As PREPO, formerly referred to as the NTPF, gained momentum as an effective means to reduce sealift response time and provide increased presence in the area, the number of ships and scope of the mission increased. The slow loading/unloading breakbulk ship was replaced with the LASH vessel.

Included under MSC long-term charter are 25 ships of the Afloat Pre-Positioning Ships (APS) Program. The program consists of two parts. The Maritime Pre-Positioning Ships (MPS) Program and the Pre-Positioning (PREPO) Ships Program (formerly Near Term Pre-Positioning Force) discussed previously.

The MPS Program is designed to combine the responsiveness of airlifted troops with sealift delivery of pre-positioned materiel. The 13 ships involved in the program will be organized into 3 MPS Squadrons that can carry equipment and supplies for Marine-amphibious brigades.

The 12 PREPO ships are assigned to Commander, MPS Squadron Two and consist of those pre-positioned cargo ships and tankers loaded with Army and Air Force equipment, POL, and supplies.

The Army has ammunition stowed on three ships in the PREPO Ships Program. Due to the requirement that the ships undergo maintenance at prescribed intervals, it is necessary to return the ship to a port on a scheduled basis to permit offloading of the ammunition prior to ships maintenance. During this period, all ammunition is subjected to rigorous inspection to determine its condition, and inventories are accomplished to verify the accountable records. Maintenance, P&P, exchange of stock, etc., are also accomplished at the same time. This fact, coupled with the need to provide safe and secure storage and adequate space for staging for backloading, restricts the number of installations at which the operation can be conducted. Most have been conducted at the U.S. Navy Magazine, Subic Bay. The slides that follow depict some highlights of the NTPF operations from August 1980 to date.

Aerial view of Military Ocean Terminal Sunny Point, NC site of 1980 onload of first ship with Army ammunition:

First ammo onload of NTPF breakbulk ship SS American Champion.

Onload complete, the Champion is ready to deploy.

The Champion arrives at NAVMAG Subic Bay January 1982 for first Army ammunition maintenance cycle which was the third NTPS maintenance cycle.

This slide shows the considerable cargo lay-down area available at Subic.

Download of ammo completed in nine days of around-the-clock operations.

With mission complete, SS American Champion departs Subic on 2 February 1982.

Inventory, inspection, P&P completed in 17 days. SS American Spartan relieves the Champion on 19 February 1982.

Backload of the Spartan took 11 days.

During the fifth maintenance cycle, NTPF transitioned from breakbulk to Lighter Aboard Ship (LASH). Here the SS Gulf Shipper and

The USNS Southern Cross discharge ammo at Subic Bay in March through April 1984.

LASH vessel SS American Veteran arrives with 63 lighters and 21 MSC vans.

Inventory, inspection, P&P, and maintenance complete, backloading to LASH barges begins.

Typical LASH barge with cargo stowed in breakbulk fashion.

LASH barge with general supplies cargo mixture.

Aerial view of Camayan Pier, Subic Bay, showing 12 LASH barges and the expanse of operations.

The previous slides depicted NTPF operations conducted at the U.S. Navy Magazine, Subic Bay R.P. as indicated earlier. The ammunition ships in the NTPF are based at Diego Garcia.

This is Diego Garcia, located in the Chagos Archipellago in the Indian Ocean. It is a 20 square mile island, forming part of the British Indian Ocean Territory (B.I.O.T.), and serves as a base for the U.S. Air Force, Navy, and MPS Fleet serving the Indian Ocean area.

This slide shows the part of Diego Garcia. The air strip is in the center and the pier is at right, extending into the harbor.

This is Central Gulf Lines' SS Green Harbour. This ship carries approximately 48 (LASH) barges. Each barge containing Army preposition stock on this vessel is 15 feet high, 30 feet wide, and 60 feet long. Each barge is stowed in breakbulk fashion and can be on/off loaded by the ship with a gantry crane. The maximum stacking on the weather deck is two barges high and up to four barges below deck.

Ammunition stored in the above-deck barges is exposed to a temperature range of 75°F to 95°F with humidity levels seldom going below 80%. All above-deck barges and barges stored in the hold are individually connected to a dehumidification system.

In order to obtain storage environmental data, five LASH barges on the Green Harbour were instrumented at Subic Bay in November, 1985. Each barge was gridded with a temperature and humidity sensor placed in each corner, mid-sidewall and center, in three layers from bottom, middle, to top. Airflow and temperature-humidity probes were placed at the barge dehumidifier inlet and exhaust. The probes are connected to a datalogger which digitally stores data from all probes every half hour. Data storage modules are changed out on a 30-day basis. Data is being collected as of 1 December 1985 and is an on-going process until the next ship's maintenance cycle. At this time, an assessment of the ammunition quality will be made to assess the effects of the storage environment.

This slide shows a combination temperature-humidity probe (the silver cylindrical housing mounted below the cross member), a hot wire anemometer (pencil-like probe) mounted at an inlet air duct of a LASH barge. The wires at right connect to a datalogger.

These dataloggers were chosen because they operated from standard "D" size flashlight batteries for a period over 30 days.

Each probe is read and the data recorded in the storage module mounted on the water-tight enclosure cover (at left).

This slide shows a datalogger installation in the hold on the Green Harbour.

This is a partially loaded LASH barge.

Our organization, USADACS, has been tasked by HQ, U.S. Marine Corps to investigate the effectiveness of vented containers in a controlled environment in MPS Squadron 2. Eight MILVANs were instrumented on the MV Bonnyman stationed at Diego Garcia. Temperature and humidity are being monitored in each MILVAN with selected ammunition items. This slide shows the probe in a small arms MILVAN.

And this one shows prop charges. Probes are placed as close to the geometrical center of the container as possible.

The dataloggers for this application operate on a five-minute interval and record the average value every half hour. Four recording instruments are used in a 60-day data recording cycle. Data recorded in storage modules are transmitted to USADACS for processing.

The ability to rapidly deploy ready forces anywhere in the world has resulted in the necessity to store UBL in configurations that violate normal compatibility standards for storage of ammunition. Due to the overriding mission requirements for centralized storage of UBLs, compatibility requirements have been somewhat relaxed.

Rapid deployment scenarios envision the need for providing all classes of supply as one package. This slide shows a contingency plan package pre-rigged for air drop to support an airborne corps. This points out not only the incompatibility among the Class V items but the obvious incompatibility with other classes of supply. Operational requirements are overriding considerations.

For OCONUS units, relaxation of normal requirements has been formalized in Chapter 10 of DOD 6055.9-STD. Use of this criteria allows the responsible major commands to fulfill their missions when requirements dictate the need to keep their UBL ammunition within the boundaries of their barracks or in the immediate vicinity thereof in trucks, trailers, tanks, structures, etc. This involves acceptance of greater-than-normal risks to unit personnel, facilities, and equipment when permitted by host nation laws and/or status of forces agreements. Essentially, this allows commanders to store up to 4,000 KG Net Explosive Quantity (NEQ) in a BLAHA, disregarding normal storage compatibility requirements, while excluding propelling charges in Class/Division 1.2 and the quantity of explosives in Class/Division 1.3 when determining NEQ for quantity-distance (QD) purposes. QD relationships in a BLAHA are prescribed by a separate QD table applicable only to basic load storage areas.

Rapid deployment of ready forces stationed in the CONUS presents another situation requiring pre-configured UBL for aerial delivery. Pre-rigged UBL, trailer mounted for airlift, also presents compatibility problems. Normal storage compatibility requirements cannot be met when storage in a central location is essential to meet rapid deployment time-workload constraints.

The following slides illustrate a typical magazine at a CONUS depot and pre-rigged loads stored:

CONUS Stradley Igloo Magazine
Anti-Personnel Mines
Small Arms Ammo
Small Arms Ammo
Mixed Loads in Storage
Small Arms in Storage
Pre-Rigged Load

A point of interest is that compatibility within vehicles and on pre-rigged pallets is consistent with requirements of TM 38-250 for air shipment and DOT compatibility requirements, but storage compatibility requirements are not met.

The next two slides are typical of UBL mixes in storage for rapid deployment.

The first slide represents UBL pre-rigged on AF 463L pallets, stored in earthcovered magazines. Note that Magazine A has a large quantity of explosives with 25,590 pounds. Incompatibility is due to the presence of 190 pounds net explosive weight (NEW) of storage compatibility group (SCG) "G" smoke grenades. These grenades are dispersed among several pre-rigged pallets due to mission signalling requirements. The SCG "D" material is permissible for storage with SCG "C" or Category Z. The incompatible SCGs are shown in red.

The next slide represents a typical UBL for a 155mm ready battery, palletized and trailer mounted. In this case, the SCG "G" primers are not compatible with SCG "D" items. Storage of SCG "C" and "D" is permissible under Category Z. This storage configuration is similar to the complete round concept. While not compatible for storage, this mix of SCGs is compatible for military air shipment in accordance with TM 38-250.

The following slides show examples of UBL pre-rigged for airdrop and trailer-mounted loads of ammunition palletized on AF 463L pallets for airlift.

Pre-Rigged for Airlift
Pre-Rigged for Airlift
Pre-Rigged for Airlift
Pre-Rigged for Airlift
Pre-Rigged for Airlift
Pre-Configured Load
Loaded Trailer
Loaded Trailer (Inside)
Loaded Trailer
Loaded Trailer

During the previous discussion, I have attempted to describe the traditional ammunition storage environment, both wholesale and retail, in the United States and overseas. I then talked about the PREPO Program and storage of ammunition for the rapid deployment force. As was evidenced during the discussion, and slides that were reviewed, the pre-positioning of ammunition and its storage for rapid deployment represent many new challenges in ammunition storage.

AUSTRALIAN CONSIDERATIONS OF
RISK CRITERIA
AT JOINT USER AIRFIELDS

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and

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AUSTRALIAN CONSIDERATIONS OF RISK CRITERIA AT JOINT USER AIRFIELDS

1. THE DEVELOPMENT OF AVIATION IN AUSTRALIA RESULTED IN A NUMBER OF AIRFIELDS BEING JOINTLY USED BY MILITARY AND CIVIL OPERATORS. THE NATO GUIDELINES FOR QUANTITY-DISTANCE CRITERIA DO NOT ADEQUATELY PROVIDE FOR JOINT-USER AIRFIELDS AND WE HAVE DETERMINED, RELUCTANTLY, THAT WE CANNOT TREAT CIVIL AIRCRAFT ON JOINT USER AIRFIELDS AS A TRANSIENT RISK.

WE HAVE ALSO CONCLUDED THAT WHILST WE SHOULD USE THE PUBLIC TRAFFIC ROUTE DISTANCES, THE MINIMUM DISTANCES SHOULD BE BASED ON THE OVERPRESSURE GENERATED BY AN EXPLOSION. THESE DETERMINATIONS WERE ARRIVED AT BY CONSIDERING THE NATURE OF THE CIVIL TRAFFIC LIKELY TO USE THE AIRFIELDS,INCLUDING INTERNATIONAL FLIGHTS, AND THE DIFFERENCES BETWEEN THE CONDITIONS THAT THE PUBLIC TRAFFIC ROUTE TABLES ARE MEANT TO COVER

AND THOSE THAT APPLY ON AN AERODROME.

2. WE INITIALLY ATTEMPTED A PROBABALISTIC APPROACH TO THE PROBLEM OF PROVIDING ADEQUATE SAFETY TO THE PUBLIC, WHEREBY WE WOULD DEFINE THE PROBABILITIES ASSOCIATED WITH AN ACCIDENT INSOFAR AS THEY RELATED TO THE LIKELY PRESENCE OF CIVILIANS, AND ENDEVOUR TO QUANTIFY THE RISKS FOR PARTICULAR SEPARATION DISTANCES. THIS APPROACH DID NOT SUCCEED DUE TO THE LACK OF CREDIBLE DATA AND THE LARGE VARIANCES THAT NEEDED TO BE APPLIED; WE HAVE SETTLED INSTEAD FOR A SUBJECTIVE APPROACH WHEREIN WE CONSIDER THE ELEMENTS WITHIN THE PROBLEM AND ENDEVOUR TO LIMIT THEIR CONSEQUENCES IN AN EXPLOSIVE ACCIDENT.

3. THE ELEMENTS THAT WE HAVE CONCENTRATED ON ARE:

A. FRAGMENTATION,

B. BLAST OVERPRESSURE, AND

C. PILOT REACTION.

WHAT WE WISH TO DO IN THIS PRESENTATION IS TO OUTLINE THE RATIONALE WE HAVE USED TO ARRIVE AT THESE ELEMENTS, DISCUSS THE QUANTIFICATIONS

THAT HAVE RESULTED FROM OUR CONSIDERATIONS AND DETAIL THE CONCLUSIONS WE HAVE TENTATIVELY ARRIVED AT.

OBJECTIVES

4. THE PRIME OBECTIVE FOR US IS THE ESTABLISHMENT OF GUIDELINES THAT DEFINE THE SAFETY PARAMETERS TO BE APPLIED AT JOINT-USER AIRFIELDS. THESE MUST BE IN ACCORD WITH THE POLICY THAT MILITARY USE OF EXPLOSIVES MUST NOT ENDANGER THE PUBLIC, NOT UNDULY INCONVENIENCE NORMAL USE OF THE AIRFIELD,WHILST NOT IMPOSING UNACCEPTABLE LIMITATIONS ON MILITARY OPERATIONS. WE HAVE AN ULTIMATE OPTION IN THAT WE COULD SIMPLY BAN CIVIL OPERATIONS THAT CONSTRAINED OUR OPERATIONAL EFFECTIVENESS, BUT AS YOU CAN APPRECIATE, SUCH A STEP COULD ONLY BE EASILY JUSTIFIED IN A DEFINED EMERGENCY, OR IN A SET OF CIRCUMSTANCES WHERE NORMAL OPERATIONS COULDNOT OTHERWISE PROCEED.

5. WE HAVE A NUMBER OF JOINT-USER AIRFIELDS WHERE WE NEED TO OPERATE WITH AGREED GUIDELINES DESIGNED TO AFFORD PROTECTION TO THE PUBLIC.

ASSUMPTIONS

6. A NUMBER OF ASSUPTIONS HAVE BEEN MADE IN THE EVOLVING OF OUR RATIONALE, THESE ARE:

A. CIVIL AIRCRAFT ON TAXIWAYS AND RUNWAYS POSE DIFFERENT RISK LEVELS WHEN EXPOSED TO THE SAME STIMULI,

B. THERE ARE FUNDAMENTAL DIFFERENCES BETWEEN THE CHARACTERISTICS OF PUBLIC TRAFFIC ROUTES AND AIRCRAFT ON AIRFIELDS, AND

C. THE MINIMA SHOULD RELATE TO OVERPRESSURE LIMITS.

7. THE IMPORTANT DIFFERENCE BETWEEN AIRCRAFT ON TAXIWAYS AND AIRBORNE IS THE CONSEQUENCES ARISING FROM A FRAGMENT STRIKE, THE AERODYNAMIC EFFECTS OF AN OVERPRESSURE WAVE AND THE POTENTIAL CRASH RISK ARISING FROM PILOT REACTION TO A DETONATION. IN EACH CASE THE EFFECTS ARE POSSIBLY DRAMATIC WHILST THE AIRCRAFT IS AIRBORNE BUT MAY BE OF LESSER CONSEQUENCE FOR AN AIRCRAFT ON THE GROUND. WE THEREFORE

PROPOSE TO APPLY A MORE CONSERVATIVE LIMIT TO RUNWAYS THAN TO TAXIWAYS.

8. THE DIFFERENCES BETWEEN VEHICULAR TRAFFIC AND AIRCRAFT ARE REASONABLY SELF-EVIDENT; THE AIRCRAFT IS UNDER THE CONTROL OF A TRAINED PILOT WHO, IN THE EXTREME CASES OF LARGE PASSENGER AIRCRAFT, CAN REASONABLY BE EXPECTED TO ACT IN A COMPETENT MANNER. IN ADDITION, ALL AIRFIELD MOVEMENTS ARE UNDER AIR TRAFFIC CONTROL SO THAT THE CHAOTIC ELEMENT ASSOCIATED WITH PUBLIC TRAFFIC ROUTES IS ABSENT. AN AIRCRAFT HOWEVER, IS MORE VULNERABLE TO A FRAGMENT STRIKE AND IF DAMAGED SUCH THAT EVACUATION IS REQUIRED THEN PASSENGER LIVES MAY INDEED BE AT RISK. ON BALANCE WE BELIEVE THAT THESE CONSIDERATIONS CANCEL EACH OTHER SUCH WHAT WE WILL USE THE PUBLIC TRAFFIC ROUTE DISTANCE TABLES BUT APPLY DIFFERENT MINIMA.

9. OF MAJOR CONCERN TO US IS THE ESTABLISHING OF AN ADEQUATE MINIMA THAT ENSURES A HIGH DEGREE OF AIRCRAFT CONTROLLABILITY WHEN BUFFETED BY THE OVER-PRESSURE WAVE BUT WHICH DOES NOT UNREALISTICALLY LIMIT OUR ABILITY TO OPERATE FROM THE BASE. THE EMPHASIS ON OVER-PRESSURE IS BASED ON OUR REVIEWS THAT SHOW THAT FRAGMENTATION DAMAGE, WHILST IT CANNOT BE ENTIRELY DISREGARDED, WILL NOT NORMALLY BE A PROBLEM; IN FACT, WHERE LARGE QUANTITIES ARE CONCERNED THE SAFETY DISTANCES ADEQUATELY CATER FOR IT. FOR SMALLER QUANTITIES HOWEVER, THE MINIMUM SAFETY DISTANCE CAN BE MOST RESTRICTIVE AND THIS LED US TO EXAMINE THE BASIS FOR THE DISTANCE MINIMA; THE OUTCOME IS THAT WE HAVE REDEFINED THE BASIS FOR THE MINIMA TO ONE THAT IS IN TERMS OF THE OVER PRESSURE THAT WOULD BE GENERATED . THIS APPROACH AIMS TO RETAIN AN ADEQUATE LEVEL OF SAFETY FOR THE PUBLIC, BOTH ON THE GROUND AND IN THE AIR, WHILST NOT UNREALISTICALLY LIMITING OPERATIONS.

I WOULD NOW LIKE TO DISCUSS THE ELEMENTS CONSIDERED IN OUR APPROACH

FRAGMENTATION

10. WE ARE AWARE THAT THE DDESB HAS PUBLISHED A STANDARD WHICH DETAILS US JOINT-USER AIRFIELD Q-D CRITERIA. HOWEVER, WE NOTE THAT

THE STANDARD USES A FRAGMENT DENSITY OF ONE HAZARDOUS FRAGMENT PER 600 SQUARE FEET AS THE CRITERION, WHERE A HAZARDOUS FRAGMENT IS DEFINED AS ONE HAVING AN ENERGY OF 58 FT LB OR GREATER. WE FEEL THAT THIS CRITERION IS NOT ENTIRELY SUITABLE AS :

A. IN OUR EXPERIENCE, AN ENERGY OF 58 FT LB IS INSUFFICIENT TO PENETRATE AN AIRCRAFT SKIN,

B. THE POPULATION DENSITY OF A PASSENGER AIRCRAFT IS FAR GREATER THAN THAT DETAILED IN THE DEFINITION, AND

C. PASSENGER AIRCRAFT MAY CONTAIN UP TO 200,000 LITRES OF FUEL.

THE LAST TWO FACTORS MAKE THE POSSIBLE CONSEQUENCES OF A FRAGMENT STRIKE ON AN AIRCRAFT MOST PROFOUND.

11. INVESTIGATIONS CONDUCTED IN AUSTRALIA, INCLUDING A COMPREHENSIVE DOCUMENT SEARCH, INDICATED THAT A CRITICAL FRAGMENT ENERGY LEVEL IS ABOUT 73 KG M (FT LB). WHILST THIS LEVEL UNDERSTATES THE PROTECTION AVAILABLE TO CRITICAL COMPONENTS, WE BELIEVE THAT IT OFFERS A REASONABLE LEVEL FOR ASSESSMENT PURPOSES WITH A BUILT-IN CONSERVATISM. BELOW THIS LEVEL, THE MECHANISM OF PENETRATION CHANGES WITH ENERGY BEING ABSORBED BY PLASTIC DEFORMATION OF THE AIRCRAFT SKIN.

12. WE HAVE NOTED ANOTHER FACTOR THAT RELATES TO CONSIDERATIONS OF FRAGMENTATION ; TRIALS CARRIED OUT AT VARIOUS FACILITIES INDICATE THAT FOR SMALL QUANTITIES-UP TO ABOUT 4500 KG NEQ THE DISTRIBUTION OF FRAGMENTS FROM AN EXPLODING BUILDING RESEMBLES SOMEWHAT OF A MALTESE CROSS; SUCH A DISTRUBION, IF CONSISTENT, MAY BE UTILIZED BY ALIGNING THE BUILDINGS TO MINIMISE POTENTIAL FRAGMENT ATTACK.

13. OVERRIDING ALL THESE CONSIDERATIONS IS THAT IF THE BASIC D11 AND D13 TABLES ARE USED, WHICH ARE OF COURSE BASED ON OVERPRESSURE EFFECTS AND THE PES IS CONSIDERED INTERCEPTOR TRAVERSED, THERE IS LITTLE DANGER FROM THE EFFECTS OF FRAGMENT ATTACK. LARGE QUANTITIES REQUIRE LARGE SAFETY DISTANCES, COMMENSURATE WITH THE HAZARD, WHEREAS

SMALL QUANTITIES ARE ADEQUATELY PROTECTED AGAINST BY TRAVERSES. OVERPRESSURE IS THEREFORE THE PRIME CONSIDERATION.

OVERPRESSURE

14. THE EFFECTS OF OVER-PRESSURE ARE NOT AS EASY TO OVERCOME AND ARE THE DRIVING CONSIDERATION FOR SMALL QUANTITIES. THE DDESB GUIDELINES TO OVER-PRESSURE DAMAGE ARE DETAILED IN DDESB STANDARD DOD 6055-9, AND ARE SHOWN IN TABLE 1. WE HAVE USED THIS GUIDE, PLUS THE GENERAL PHILOSOPHY OF THE UK ESTC LEAFLETS, AS THE STARTING PJOINT FOR OUR CONSIDERATIONS OF REASONABLE OVER-PRESSURE LIMITS.

15. AFTER SOMEWHAT PROTRACTED NEGOTIATIONS AND ANALYSIS OF CONDITIONS, WE HAVE SETTLED FOR FIGURES FOR GUIDANCE TO LICENCING AUTHORITIES THAT ARE LOWER THAN THOSE IN THE DDESB GUIDE. THE LEVELS WE HAVE SET ARE STILL SUBECT TO YET MORE CONSULTATION AND CONSIDERATION BUT WE SEEM TO BE REACHING A REASONABLE COMPROMISE THAT AFFORDS A HIGH LEVEL OF PROTECTION TO CIVILIAN USERS OF JOINT-USER AIRFIELDS, WHILST NOT UNDULY AFFECTING NORMAL OPERATIONS.

16. THE LIMITS WE HAVE PRESENTLY SETTLED ON ARE THE D13 PUBLIC TRAFFIC ROUTE DISTANCES WITH THE FOLLOWING MINIMA:

A. 50 MILLIBARS (0.72 PSI) AT THE CENTRELINE OF THE RUNWAY, AND

B. 70 MILLIBARS (1.0 PSI) AT THE CENTRELINE OF TAXIWAYS.

IN SETTING THESE LEVELS WE FULLY REALISE THAT WE HAVE MADE NO ALLOWANCE FOR THE EFFECTIVENESS OF FIRE SERVICES, THE POSSIBILITY OF PRESSURE REDUCING OR ENHANCING STRUCTURES, OR THE PRECISE INFLUENCE OF AIRCRAFT TYPE.

PHYSYCHOLOGICAL EFFECTS

17. WE KNOW OF NO STUDY THAT WOULD GIVE US A GUIDE TO THE REACTION OF PILOTS IN GENERAL TO AN EXPLOSION OCCURING IN THE VICINITY OF THEIR AIRCRAFT. COMMON SENSE INDICATES THAT THERE WILL BE CONSEQUENCES ESPECIALLY WITH PRIVATE PILOTS, BUT THAT AIRLINE PILOTS ARE MORE LIKELY TO BE ABLE TO RAPIDLY REDRESS DETRIMENTAL EFFECTS. THE LIKELY REACTIONS DISCUSSED EARLIER IN THIS PRESENTATION HAVE BEEN

BORNE IN MIND THROUGHOUT OUR DELIBERATIONS WITHOUT ANY ATTEMPTS BEING MADE TO QUANTIFY THE EFFECTS FURTHER.

SUMMARY Royal Australian Air Force

18. (RAAF) OPERATIONS AT SOME AUSTRALIAN AIRFIELDS ARE COMPLICATED BY THE AIRFIELD'S JOINT-USER STATUS. WE HAVE ENDEVOURED TO STRIKE A BALANCE BETWEEN THE LEGITIMATE NEEDS OF THE PUBLIC FOR SAFE ACCESS TO THESE AIRFIELDS WHILST MAINTAINING OUR AIM OF ENSURING THAT OUR OPERATIONS ARE NOT UNDULY AFFECTED. OUR INITIAL ATTEMPTS TO UNDERTAKE A PROBABALISTIC APPROACH FOUNDERED ON THE LACK OF DATA, AND WE RESORTED TO A SOMEWHAT SUBJECTIVE APPROACH.

19. THE RISK PROBLEMS WERE ASSESSED AS DUE TO FRAGMENTATION, BLAST OVER-PRESSURE AND THE PHYSCHOLOGICAL EFFECTS OF AN EXPLOSION. OF THESE, OVER-PRESSURE ASSUMED THE MORE IMPORTANT CONSIDERATION DUE TO THE EFFECT OF THE IMPULSE WAVE ON AIRCRAFT. WE CONSIDER THAT WE ARE APPROACHING REASONABLE LEVELS THAT ALLOW FOR OUR TWIN AIMS OF MAINTAINING PUBLIC SAFETY AND RETAINING OPERATIONAL CAPABILITY. HOWEVER, WE DO NOT AT THIS TIME FEEL ENTIRELY COMFORTABLE WITH OUR CONCLUSIONS AND WOULD BE MOST INTERESTED IN ANY THOUGHTS OTHER NATIONS MAY HAVE ON THIS TOPIC.

HAZEL - "A COMPUTERIZED APPROACH TO SYSTEM SAFETY"

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HAZEL is a computerized approach to system safety, whose design incorporates the use of new concepts for hazard evaluation of a system.

These concepts are based on the postulate that an incident results when during the exposure of a given hazard stimulus within a system, the stimulus permits the conversion and release of potential energy outside of the design parameters. Depending on which set of events follows this release of energy, one of several possible consequences can result. The severity of this consequence is dependent on which set of events occurs. Further, it is possible that this set of events could be a null set, producing no consequences.

The goal of Systems Safety Engineering is to maximize the operational effectiveness of a system by identifying hazards within the design of the system, which will impair its operational effectiveness, in order to recommend timely corrective actions which are cost effective. Unlike other elements of engineering, Systems Safety Engineering does not produce absolutes but produces reduced probabilities. Yet like other elements of engineering, Systems Safety Engineering is faced with the same constraints - time, lack of personnel and money.

Therefore to fulfill the goal of Systems Safety Engineering, the Systems Safety Engineer must have tools which provide the project manager with decision making information and solutions, not problems, in the most cost effective manner.

To provide the Ammunition Peculiar Equipment (APE) project managers at U.S. Army Defense Ammunition Center and School (USADACS), Equipment Division (DEN), with decision making information and solutions, the concepts, hazard analysis formats and definitions of Military Standard (MIL-STD) 882A, System Safety Program Requirements, 28 June 1977, were reviewed along with other literature available on systems safety engineering. This review combined with the experience gained in analyzing the safety of APE, lead to the development of new concepts, definitions and hazard formats. The nucleus of this development is a modification of the work of William T. Fine presented in his paper on "Mathematical Evaluations For Controlling Hazards", Naval Ordnance Laboratory Technical Report 71-31 of 8 March 1971.

The first step in developing a solution was to review MIL-STD 882A. The standard recommends the use of two classifications in determining the risk involved with a system for a particuliar hazard -- the probability that a hazard will result in a mishap and the worst potential consequence of that mishap. The standard further recommends the use of six categories to define hazard probability and four categories to define severity.

While the techniques of MIL-STD 882A do provide for recognition of safety deficiencies, it does not provide a realistic representation of the hazard to mishap mechanism nor the mechanics necessary for safety personnel to be able to make recommendations on which deficiencies are the most critical or how to correct them in the most cost effective method.

The standard states that the severity of a mishap is not dependent on the probability of the hazard, only on its consequences. Therefore even if the hazard is removed from the system, the consequences are still the same, although impossible to occur. Therefore, only the probability of the accident can be dealt with by systems safety engineering and the project manager.

The standard defines a hazard as "an existing or potential condition that can result in a mishap." In order for a hazard to result in a mishap, the hazard must be considered capable of doing work. If it is capable of doing work, it must then contain potential energy. Therefore, a hazard can be considered potential energy existing within the system or its environment.

However, in order for a system to complete its mission, it must be capable of doing work, and therefore capable of converting potential energy into work. Therefore, the presence of potential energy within a system alone, does not cause a mishap. It is when the potential energy is converted to work and released in an uncontrolled way that a mishap occurs. The more often the potential energy is capable of being converted, the greater the likelihood of it being released in an uncontrolled way.

Therefore, the potential energy is not the problem. The problem is how often that potential energy is present and how that potential energy can be converted and released outside of the design parameters. From this rationale, two new concepts were identified and defined. The first being STIMULUS and the second being STIMULUS EXPOSURE.

Stimulus represents the mechanism through which the potential energy can be converted and released outside of the design parameters.

Stimulus Exposure is a measure of how often the stimulus is present within the system or its environment.

From experience it can be seen that when potential energy is released in an uncontrolled manner, it does not always result in a mishap. Often the release of the potential energy will result in nothing happening or in a near miss. Therefore, a mishap takes more than the uncontrolled release of potential energy to occur. Not only must the potential energy be released outside of design parameters, but a particular set of events or event must occur. If a given event or sequence of events does not occur, then a given mishap outcome will not occur. From this, two additional concepts were identified and defined, MISHAP SET and MISHAP PROBABILITY.

Mishap Set is the event or events which must take place in order for a given mishap to occur. Furthermore for any given uncontrolled release of potential energy, more than one mishap set and outcome exist.

Mishap Probability is the likelihood of a particular mishap sequence occurring to completion.

Based on the above discussion, the hazard-mishap mechanism can be defined as follows and serve as a postulate for further development:

> An incident results when during the exposure of a given hazard stimulus within a system, the stimulus permits the conversion and release of potential energy outside of the design parameters. Depending on which mishap set follows this release of energy, one of several possible consequences can result. The severity of this consequence is dependent on which mishap set occurred. Further, it is possible that this mishap set could be a null set, producing no consequences.

Once the postulate was stated and accepted, it became necessary to formally define the new concepts and establish qualitative levels. The qualitative levels are defined in Appendix A.

Maximum Credible Mishap (MCM). The most credible catastrophic effect on personnel, production activities, or facilities due to the occurrence of a particular event or series of events. The MCM has an occurrence probability of 1 if a given event or series of events occurs.

Stimulus. The mechanism through which potential energy, existing within a system, operation, facility, or environment, may be converted and released outside of the design parameters.

Stimulus Exposure. The likelihood, expressed in quantitative or qualitative terms, that a given stimulus could be present within a system, operation, or facility. The greater the likelihood of the stimulus, the greater the likelihood of its associated potential energy being released. The stimulus exposure is dependent on the presence of the stimulus and is independent of all other factors.

Mishap Set. A realistic statement of the sequence of events or event which must occur in order for the MCM to happen.

Mishap Set Probability. The likelihood, expressed in quantitative or qualitative terms, that the stated MCM Mishap Set can occur. The mishap set probability is dependent on its likelihood of occurring and is independent of all other factors.

Severity. A qualitative assessment of the degree of injury, occupational illness, property or equipment damage associated with the MCM. Severity is dependent only on the MCM. Once established, it does not change, only its Mishap Set Probability can change.

Criticality. A mathematical combination of the stimulus exposure, mishap set probability, and severity. Criticality serves to facilitate the ranking of possible recognized hazards to determine priority of action and allotment of funds.

Safety Cost Factor. The estimated dollar cost of the proposed method of eliminating, reducing, or controlling a safety deficiency. This value is used in the Safety Cost/Benefit Analysis.

Degree of Safety Correction. The estimated reduction in the likelihood of the stimulus exposure and/or the mishap set probability. This value is used in a Safety Cost/Benefit Analysis.

Risk. The expected value of loss.

Risk Acceptability. That level of risk which has been determined as acceptable in order to fulfill mission requirements. It represents a level of risk where either the output of resources to rectify safety deficiencies does not result in a proportional increase in system safety; or so restricts the performance of the system, it cannot fulfill its assigned mission. USADACS-DEN uses a criticality of 10 or less as acceptable risk. Any risk acceptance greater than a criticality of 10, requires a Safety Cost/Benefit Analysis to document it rationale for acceptance.

Implementing this postulate of hazard-mishap mechanism, allows a system to be analyzed using these new techniques:

1. Identify the types of potential energy which could exist as a possible hazard within the system or its environment;

2. Identify what condition could convert this potential energy and release it outside of the design parameters, stimulus;

3. Determine how often the stimulus is present with the system, stimulus exposure;

4. Identify the most credible, catastrophic result from the release of potential energy, maximum credible mishap;

5. Define the event or sequence of events which must occur for the maximum credible mishap to happen, mishap set;

6. Determine the likelihood of the mishap set occurring, mishap set probability;

7. Rank the hazard with respect to the other recognized hazards, criticality.

An additional technique provided the safety engineer, once the criticality of the safety concern has been established, is the capability of being able to perform a cost/benefit analysis to determine if possible corrective actions are economically beneficial and if they are, which has the greatest cost to benefit ratio.

$$\text{Justification} = \frac{\text{Criticality}}{\text{Cost Factor X Degree of Correction}}$$

Once the concepts were identified, the terms defined, and qualiatitive levels established, the next step was to devise hazard analysis formats which would incorporate the use of the new concepts.

Past experience with the system safety of APE, had demonstrated that three general types of hazard analysis had proven effective.

The first type was basically a preliminary hazard analysis type. DEN had used four variations of this type with each variation providing a more detailed review of the equipment. They were:

1. A preliminary type variation used at concept development;

2. A system type variation used as the design progressed;

3. A sub-system type variation, if required by the complexity of the APE, used as the system's design advanced;

4. A component type variation used when necessary for extremely complex systems.

The second type of analysis which had proven effected was the Operation and Support Hazard Analysis. This analysis had proven effective not only in the analyze of the APE, but had, also, been used when developing Standing Operating Practices (SOP) for engineering tests.

The final type of analysis was the Failure Modes and Effects Analysis (FMEA). The FMEA, while not as rigorous of analysis as a Fault Tree, does provide results which are useful and can be completed with far less expenditure of man hours, especially when production of only one of two units of APE is involved. The April 1968 issue of "Discover" magazine contains a discussion on FMEA and Fault Tree Analysis in an article titled "They Fly In The Face Of Danger".

However in order to stay consistent with the criticality of other analyses, the method of determining the criticality for the FMEA had to be revised. This was accomplished by defining the criticality for the FMEA as:

CRITICALITY = Usage X Failure Rate X Replicaation Factor X Severity

where:

Usage is a measure of the number of times the component must perform within the system;

Failure Rate is an assessment of the probability of failure during a given time period;

Replication Factor is a measure of redundancy within the system;

Severity is a measure of the consequences of the failure.

The qualitative levels for each of the factors, used by DEN, are contained in Appendix B.

As a prerequisite, it was decided that the format should provide more information than was currently included on the hazard analysis formats. The format should serve to document the complete history of the possible safety deficiency - its status, what was done to correct it, what type of system safety precedence should be used to correct the deficiency, and how this effected its probability of occurrence.

Further, since the proposed information would provide more than just the recognition of hazards, it was decided to call them "Safety Analysis".

In order to accommodate this information, it was realized that one page would be required for each possible safety deficiency recognized.

Based on the above, a format was designed by DEN which provided one page for each safety deficiency, and consisted of four sections of information:

1. Safety deficiency status information;

2. System information;

3. Safety deficiency information;

4. Disposition information.

The final formats for each of the different types and variations of types are contained in Appendix C.

The safety deficiency status information section composes the top section of the page and remains constant for all the safety analysis formats used. It contains the following information:

1. It contains the date the page was last printed;

2. The page number of the safety analysis of which it was a part;

3. The date the safety deficiency was first recongized as possible and opened;

4. The hazard tracking number, HAZTAC, for that individual APE, assigned when opened;

5. Indication whether or not the safety deficiency has been addressed and closed, and if closed, has the correction been verified as incorporated into the design and/or manual;

6. The APE number assigned;

7. The APE title assigned;

8. The name of the project manager assigned;

9. The name of the safety evaluator performing the safety analysis.

The next section of the page consists of the system information. The amount of information in this section varies depending on the type of safety analysis being performed. However, the amount of information provided is consistent with the degree to which the APE is being analyzed.

The third section documents the safety deficiency, which was determined could occur within the APE. It, also, includes a possible solution which the project manager can consider in rectifying the deficiency.

The final section provides documentation of the corrective action ultimately selected. It indicates what type of system safety precedence this action represented, the effect its use had on the criticality, and the type of result achieved.

While the new concepts, techniques, and safety analyses provided new tools for use during the design of APE, along with complete documentation of the system safety effort, one of the original goals - cost effective and timely manner - had not been achieved.

In order to achieve this goal, a series of computer programs were designed and written. These programs or modules where designed to be chained together forming one large computer program, called HAZEL. HAZEL stands for HAZard EvaLuation program. Using this technique, HAZEL could constantly be upgraded by the addition of different modules to meet future needs.

HAZEL was designed and written as a tool to be used for system safety. Therefore, it was designed to be user friendly. This was accomplished through the use of menu-driven programs (menus and program flow are contained in Appendix D) which flow from one menu to another, always allowing return to the previous menu, until arriving at the task to be performed.

To facilitate maximum use of memory for each module, to permit use of library routines, to provide maximum documentation in the program listing, and to accomplish a faster execution time, Cbasic by Digital Research was selected as the language due to it being a compiler Basic rather than an interpretive Basic. Further, Cbasic performs error checking on the source code before translating the code into an intermediate program. This helps eliminate "bugs" with in the program.

HAZEL was designed and written for the Kaypro II computer and an Epson FX-80 printer. However, Cbasic is available for computers based on the INTEL 8080, 8085 or the Zilog Z80 microprocessors using CP/M, MP/N or CP/NET operating systems.

Currently, HAZEL consists of approximately 15 modules and has been in use for six months. The major "bugs" have been worked out of the system. However, a few minor "bugs" may still exist within the system, which have not yet been discovered.

HAZEL's programs are presently contained on two program diskettes. The programs indicate when to change from one disk to the other and incorporate checking routines to insure the correct program disk is in place.

For each system being analyzed, HAZEL requires a maximum of eight diskettes. Six of these diskettes are for each of the six safety analysis which can currently be done by HAZEL.

Each analysis is contained on a separate diskette. This was done to allow the maximum number of individual records for each safety analysis file to be created. The maximum number of hazards which can be currently addressed by any one analysis is approximately 191. However, future development plans call for this number to be increased to 500 hazards per analysis. This would allow a total of 30,000 hazards per system to be recognized and tracked by HAZEL.

One of the two remaining diskettes, consist of a summary of each of the safety deficiencies from the other six diskettes and is used to provide hazard tracking of all recognized hazards.

The last diskette is used for general purpose files and the Safety Assessment Report file.

However, only two diskettes are initially required by HAZEL when a system file is created. They are the Safety Assessment File diskette, SAR, and the hazard tracking diskette, HAZTAC.

During the design of HAZEL, it was decided to incorporate a hazard checklist. The checklist used, was an extended version of the "Hazard Review Checklist" from the appendix of Handbook Of System And Product Safety by Willie Hammer. However to allow greater flexibility, the checklist was designed with two additional features and is contained on a separate diskette.

The first checklist feature allows each category of the hazard checklist to be reworded to better describe the system under going analysis.

The second checklist feature allows each category of the hazard checklist to be expanded. This allows the checklist to grow based on insight gained from experience and to be tailored to specific types of systems.

Another feature which was included in the design of the program was the ability to produce labels. Ten different labels are produced by HAZEL when a new system is started. The ten labels include one for each type of diskette used by HAZEL, plus one label to be used on the outside of the diskette container, and one to be used on a file folder.

In order to fulfill the goal - cost effective and timely manner, HAZEL prints each page of every analysis, as it is performed. Therefore as each safety deficiency is recognized, it is documented on 8-1/2 by 11 continuous form paper. This documentation can then be given to the project manager for his disposition. Further, when the safety deficiency is addressed, an updated copy of the safety deficiency page can be returned and used to update that page of the analysis. This then produces a new page of documentation, showing whether or not additional consideration is required by the program manager.

Secondly at any give time, a HAZTAC report can be produced for any system, which ranks all safety deficiencies by their criticality. The report indicates which safety analysis indicated the deficiency, its status as to open, closed or closed and verified, its page number, the type of hazard, type of action used, and result of that action used. Further, it provides a summary of all the hazards.

This summary provides the numbers and percentages for all the safety deficiencies by four classifications of information. It first classifies the safety deficiencies by whether they are open, closed, or closed and verified. Then is classifies the safety deficiencies by the safety precedence used. The third classification is by the type of result obtained by the action used. The final classification is by the type of action which should be used based on the degree of criticality.

Two additional evaluations have been added to HAZEL, since its original design. They are evaluations of the electrical environment and the APE's machine safeguarding.

Due to the nature of APE, an evaluation was added which could be used during the concept phase to classify and document electrical requirements for the type or types of environments in which the APE would be perfroming. Thereby reducing the cost, due to over designing of the electrical system.

This classification of electrical environments is based on the U.S. Army Materiel Command's Safety Manuals, AMC-R 385-100, Ernest C. Magison's book, Electrical Instruments In Hazardous Locations, and The National Electrical Code Handbook.

The evaluation of the machine's safeguarding is based on a modified checklist developed by the U.S. Department of Labor's Occupational Safety and Health Administration and published in Concepts And Techniques of Machine Safeguarding, OSHA 3067.

This modified checklist is, also, included in a recently developed inhouse publication by this author, entitled Machine Safeguarding Design Criteria For Ammunition Peculiar Equipment. This publication was developed to aid DEN designers, so that safeguarding was done during the design process, rather than as an after thought.

A final feature which was incorporated into the development of HAZEL was compatibility with two commercially available software packages which are standard software on the Kaypro II. They are "Wordstar" and "The Word". "The Word" allows HAZEL's files to be checked and corrected for spelling errors. "Wordstar" provides capability to correct typographical errors, edit files, and, also, to reestablish record's lengths changed by "The Word".

During the six months since the use of the new concepts, system safety formats, and HAZEL in DEN, system safety has been able to be more responsive to the needs of the program manager and the APE program.

The new concepts provide the program manager and safety engineer with new tools to eliminate safety deficiencies with in a system. The safety deficiency can now, either be eliminated by changing the exposure of the stimulus within the system or interrupting the mishap set to produce either a null set or acceptable risk.

The use of criticality has provided a new tool in determining which safety deficiencies are most likely to incur the greatest total loss over the life of a system. Thereby, permitting allotment of funds proportionally.

HAZEL has eliminated the time-consuming hand writing of the analysis; and then waiting for the draft to appear at the top of the clerical person's pile, in order to have legible copies.

HAZEL takes advantage of what a computer does best - repetitive tasks such as copying, filing, sorting, memorizing, and printing; while allowing the user to think, evaluate and create.

APPENDIX A

Definition of Qualitative Levels

STIMULUS EXPOSURE

The following qualitative levels were defined to express the likelihood of stimulus exposure, along with its symbol used on the analyses, and contribution value to criticality.

1. The stimulus occurs continuously or many times daily. It is assigned the symbol "A" and a value of 10.

2. The stimulus occurs frequently or approximately once per week. It is assigned the symbol "B" and a value of 6.

3. The stimulus occurs occasionally or from once per week to once per month. It is assigned the symbol "C" and a value of 3.

4. The stimulus is unusual or from once per month to once per year. It is assigned the symbol "D" and a value of 2.

5. The stimulus is rare, but has been known to occur. Its assigned symbol is "E" and a value of 1.

6. The stimulus is remotely possible but it has not been known to occur. Its assigned symbol is "F" and a value of 0.5.

7. The stimulus cannot physically occur. Its assigned symbol is "G" and a value of 0.0.

MISHAP SET PROBABILTY

The following qualitative levels were defined to express the likelihood of the occurence of the mishap set, along with its symbol used on the analyses and criticality contribution value.

1. The complete mishap set is the most likely and expected result, if the potential energy is converted and released by the stimulus. Its assigned symbol is "a" and a value of 10.

2. The complete mishap set is quite possible, not unusual, has an even 50/50 chance, if the potential energy is converted and released by the stimulus. Its assigned symbol is "b" and a value of 6.

3. The complete mishap set would be an unusual sequence or coincidence, if the potential energy is converted and released by the stimulus. Its assigned symbol is "c" and a value of 3.

4. The complete mishap set would be a remotely possible coincidence if the potential energy is converted and released by the stimulus. Its assigned symbol is "d" and a value of 1.

5. The complete mishap set has never happened after many years of exposure, but is conceivably possible if the potential energy is converted and released by the stimulus. Its assigned symbol is "e" and a value of 0.5.

6. The complete mishap set is practically impossible to occur, if the potential energy is converted and released by the stimulus. Its assigned symbol is "f" and a value of 0.1.

7. The complete mishap set is impossible to occur if the potential energy is converted and released by the stimulus. Its assigned symbol is "g" and its assigned value is 0.0.

SEVERITY

The following qualitative levels were defined to express the severity of the mishap, along with its symbol used on the analyses and its criticality contribution value.

1. Catastrophe - Numerous fatalities, damage over $1,000,000. Its assigned symbol is "I" and the value of 100.

2. Severe - Multiple fatalities; damage $500,000 to $1,000,000, or loss of APE. Its assigned symbol is "II" and a value of 50.

3. Critical - Fatality, damage $100,000 to $500,000 or more than 30 days to repair the APE. Its assigned symbol is "III" and a value of 25.

4. Serious - Extremely serious injury (permanent disability), damage $1,000 to $100,000 or repair of APE requiring one week to 30 days. Its assigned symbol is "IV" and a value of 15.

5. Marginal - Disabling injury (temporary total disability), damage up to $1,000 or repair to APE requiring more than eight hours to one week. Its assigned symbol is "V" and a value of 5.

6. Negligible - Injury requiring first aid or minor supportive medical treatment not causing lost work days or restricted work activities, correctable end item damage, or damage to APE repairable in eight hours or less. Its assigned symbol is "VI" and a value of 1.

7. None - No injury or damage. Its assigned symbol is "VII" and a value of 0.0.

SAFETY CORRECTION FACTOR

The following qualitative levels were defined to express the safety correction factor, along with its symbol used on the Safety Cost/Benefit analysis and its contribution value.

1. A reduction in either stimulus exposure or mishap set probability resulting in one level of reduction. Its assigned symbol is "1" and a value of 6.

2. A reduction in either stimulus exposure or mishap set probability resulting in a combined reduction of two levels. Its assigned symbol is "2" and a value of 5.

3. A reduction in either stimulus exposure or mishap set probability resulting in a combined reduction of three levels. Its assigned symbol is "3" and a value of 4.

4. A reduction in either stimulus exposure or mishap set probability resulting in a combined reduction of four levels. Its assigned symbol is "4" and a value of 3.

5. A reduction in either stimulus exposure or mishap set probability resulting in a combined reduction of five levels. Its assigned symbol is "5" and value of 2.

6. A reduction in either stimulus exposure or mishap set probability resulting in a combined reduction of six levels. Its assigned symbol is "6" and a value of 1.

SAFETY COST FACTOR

The following qualitative levels were defined to express the safety cost factor along with its symbol used on the Safety Cost/Benefit analysis and its contribution value.

1. Cost estimated to correct is over $50,000. Its assigned symbol is "A" and a value of 10.

2. Cost estimated to correct is $25,000 to $49,999. Its assigned symbol is "B" and a value of 6.

3. Cost estimated to correct is $10,000 to $24,999. Its assigned symbol is "C" and a value of 4

4. Cost estimated to correct is $1,000 to $9,999. Its assigned symbol is "D" and a value of 3.

5. Cost estimated to correct is $100 to $999. Its assigned symbol is "E" and a value of 2.

6. Cost estimated to correct is $1 to $99. Its assigned symbol is "F" and a value of 1.

APPENDIX B
DEFINITION OF FMEA QUALITATIVE LEVELS

Failure Modes

The following failure modes are automatically considered during the evaluation.

a. Premature operation.

b. Failure to operate at a prescribed time.

c. Intermittent operation.

d. Failure to cease operation at a prescribed time.

e. Loss of output or failure during operation.

f. Degraded output or operational capability.

g. Other unique failure as:

Usage Rate Factor

The following qualitative levels were defined to express the usage of the unit being evaluated, along with their symbol used on the analysis, and value contributed to criticality.

a. The mechanism is a safety device or life support system. Value is 10.0. Symbol used is SD.

b. The mechanism is used continuously, every system cycle. Value is 10.0. Symbol used is i.

c. The mechanism is used frequently, every other system cycle. Value is 5.0. Symbol used is ii.

d. The mechanism is used occasionally, or at least once per day or eight hours of use.Value is 2.5. Symbol used is iii.

e. The mechanism is seldom used, or only under special circumstances. Value is 1.0. Symbol used is iv.

f. The mechanism is rarely used, or only used as back-up. Value is 0.5. Symbol used is v.

g. The mechanism is never used, but does have a purpose. Value is 0.1. Symbol used is vi.

h. The mechanism has no operational function. Value is 0.0. Symbol used is vii.

Failure Rate Factor

The following qualitative levels were defined to express the failure rate of the unit being evaluated, along with its symbol used on the analysis, and value contributed to criticality.

a. The mechanism will fail at least once per shift or 8 hours of use. Value to 10. Symbol used is a.

b. The mechanism will fail at least once per week or 40 hours of use. Value to 8. Symbol used is b.

c. The mechanism will fail at least once per month or 172 hours of use. Value to 6. Symbol used is c.

d. The mechanism will fail at least once per year or during the first 1040 hours of use. Value to 3. Symbol used is d.

e. The mechanism will fail at least once in 2 years or during the first 2080 hours of use. Value to 2. Symbol used is e.

f. The mechanism is extremely reliable, will last longer than 2 years or 2080 hours of usage. Value is 1. Symbol used is f.

g. The mechanism has never been known to fail, but failure is conceivably possible. Value is 0.5. Symbol used is g.

h. The mechanism's design is such, that it is practically impossible for it to fail. Value is 0.1. Symbol used is h.

i. The mechanism's design is such, that it is physically impossible for it to fail. Value is 0. Symbol used is j.

Redundancy (R) Factor

The following qualitative levels were defined to express the redundancy factor of the unit being evaluated, along with its symbol used on the analysis, and value contributed to criticality. The values used when there is a redundant unit are based on a failure rate of 0.75. This was chosen to represent a realistic, yet very conservative value.

a. No redundancy of mechanism. Value is 1.0. Symbol used is 0.

b. One redundant mechanism is used. Value of 0.0625. Symbol used is 1.

c. Two redundant mechanisms are used. Value of 0.0156. Symbol used is 2.

d. Three redundant mechanisms are used. Value is 0.0004. Symbol used is 3.

e. Mechanism eliminated by re-design. Value is 0. Symbol used is 4.

Severity Factor

The following qualitative levels were defined to express the severity of the resultant effect on the system due to the failure of the unit being evaluated, along with their symbol used on the analysis, and value contributed to criticality.

a. CATASTROPHE: Numerous fatalities; damage over $1,000,000; major disruption of activities, loss of production facilities. Value is 100. Symbol used is I.

b. SEVERE: Multiple fatalities; damage $500,000 to $1,000,000 or loss of APE. Value is 50. Symbol used is II.

c. CRITICAL: Fatality, damage $100,000 to $500,000 or requiring more than 30 days to repair the APE. Value is 25. Symbol used is III.

d. SERIOUS: Extremely serious injury (permanent disability); damage $1,00 to $100,000; or repair of APE requiring one week to 30 days. Value is 15. Symbol used is IV.

e. MARGINAL: Disabling injury (temporary total disability); damage up to $1,000; or repair of APF requiring up to one week. Value is 5. Symbol used is V.

f. NEGLIGIBLE: Injury requiring first aid or minor supportive medical treatment not causing lost workdays or restricted work activities or correctable end item damage or damage to APE accepted as incident to operation. Value is 1. Symbol used is VI.

NONE. No injury or damage. Value is 0. Symbol is VII.

APPENDIX C

SAFETY ANALYSIS FORMATS

PRELIMINARY SAFETY ANALYSIS

Date: **Page**

Date Opened:

HAZTAC No. **STATUS CLOSED ( )** **VERIFIED ( )**

APE No. **Title:**

P.M. **Evaluated by**

System:

Hazard:

Stimulus:

Maximum Credible Mishap:

Mishap Set:

1
2
3
4
5
6
7
8

Initial
Exposure **Probability** **Severity** **Criticality**

Recommended Corrective Action:

Actual Corrective Action:

Final
Exposure **Probability** **Severity** **Criticality**

Type Action: DESIGN ( ) SAFETY DEVICE ( ) WARNING DEVICE ( ) PROCEDURE ( )

RESULT: ELIMINATED ( ) REDUCED ( ) CONTROLLED ( ) TRADE-OFF ( )

SYSTEM SAFETY ANALYSIS

Date: **Page**

Date Opened:

HAZTAC No. **STATUS CLOSED ( ) VERIFIED ( )**

APE No. **Title:**

P.M. **Evaluated by**

System:

Hazard:

Stimulus:

Maximum Credible Mishap:

Mishap Set:

1
2
3
4
5
6
7
8

Initial
Exposure **Probability** **Severity** **Criticality**

Recommended Corrective Action:

Actual Corrective Action:

Final
Exposure **Probability** **Severity** **Criticality**

Type Action: DESIGN ( ) SAFETY DEVICE ( ) WARNING DEVICE ( ) PROCEDURE ( )

RESULT: ELIMINATED ( ) REDUCED ( ) CONTROLLED ( ) TRADE-OFF ( )

SUB-SYSTEM SAFETY ANALYSIS

Date: **Page**

Date Opened:

HAZTAC No. **STATUS CLOSED ( )** **VERIFIED ( )**

APE No. **Title:**

P.M. **Evaluated by**

System:
Sub-System:

Hazard:

Stimulus:

Maximum Credible Mishap:

Mishap Set:

1
2
3
4
5
6
7
8

Initial Exposure	Probability	Severity	Criticality

Recommended Corrective Action:

Actual Corrective Action:

Final Exposure	Probability	Severity	Criticality

Type Action: DESIGN ( ) SAFETY DEVICE ( ) WARNING DEVICE ( ) PROCEDURE ( )

RESULT: ELIMINATED ( ) REDUCED ( ) CONTROLLED ( ) TRADE-OFF ( )

COMPONENT SAFETY ANALYSIS

Date: Page

Date Opened:

HAZTAC No. STATUS CLOSED ( ) VERIFIED ( )

APE No. Title:

P.M. Evaluated by

System:
Sub-system:
Component:

Hazard:

Stimulus:

Maximum Credible Mishap:

Mishap Set:

1
2
3
4
5
6
7
8

Initial Exposure	Probability	Severity	Criticality

Recommended Corrective Action:

Actual Corrective Action:

Final Exposure	Probability	Severity	Criticality

Type Action: DESIGN ( ) SAFETY DEVICE ( ) WARNING DEVICE ( ) PROCEDURE ( )

RESULT: ELIMINATED ( ) REDUCED ( ) CONTROLLED ( ) TRADE-OFF ( )

OPERATING AND SUPPORT SAFETY ANALYSIS

Date: Page

Date Opened:

HAZTAC No. STATUS CLOSED ( ) VERIFIED ( )

APE No. Title:

P.M. Evaluated by

Operation/Support:

Purpose:

Hazard:

Stimulus:

Maximum Credible Mishap:

Mishap Set:

1
2
3
4
5
6
7
8

Initial
Exposure Probability Severity Criticality

Recommended Corrective Action:

Actual Corrective Action:

Final
Exposure Probability Severity Criticality

Type Action: DESIGN ( ) SAFETY DEVICE ( ) WARNING DEVICE ( ) PROCEDURE ( )

RESULT: ELIMINATED ( ) REDUCED ( ) CONTROLLED ( ) TRADE-OFF ( )

FAILURE MODE AND EFFECTS SAFETY ANALYSIS

Date: Page

Date Opened:

HAZTAC No. STATUS CLOSED ( ) VERIFIED ( )

APE No. Title:

P.M. Evaluated by

Component:

Purpose:

Failure Mode:

Effect on Component

Effect on Sub-system:

Effect on System:

Initial Usage: Fail Rate: R.F.: SEV: Criticality

Recommended Corrective Action:

Actual Corrective Action:

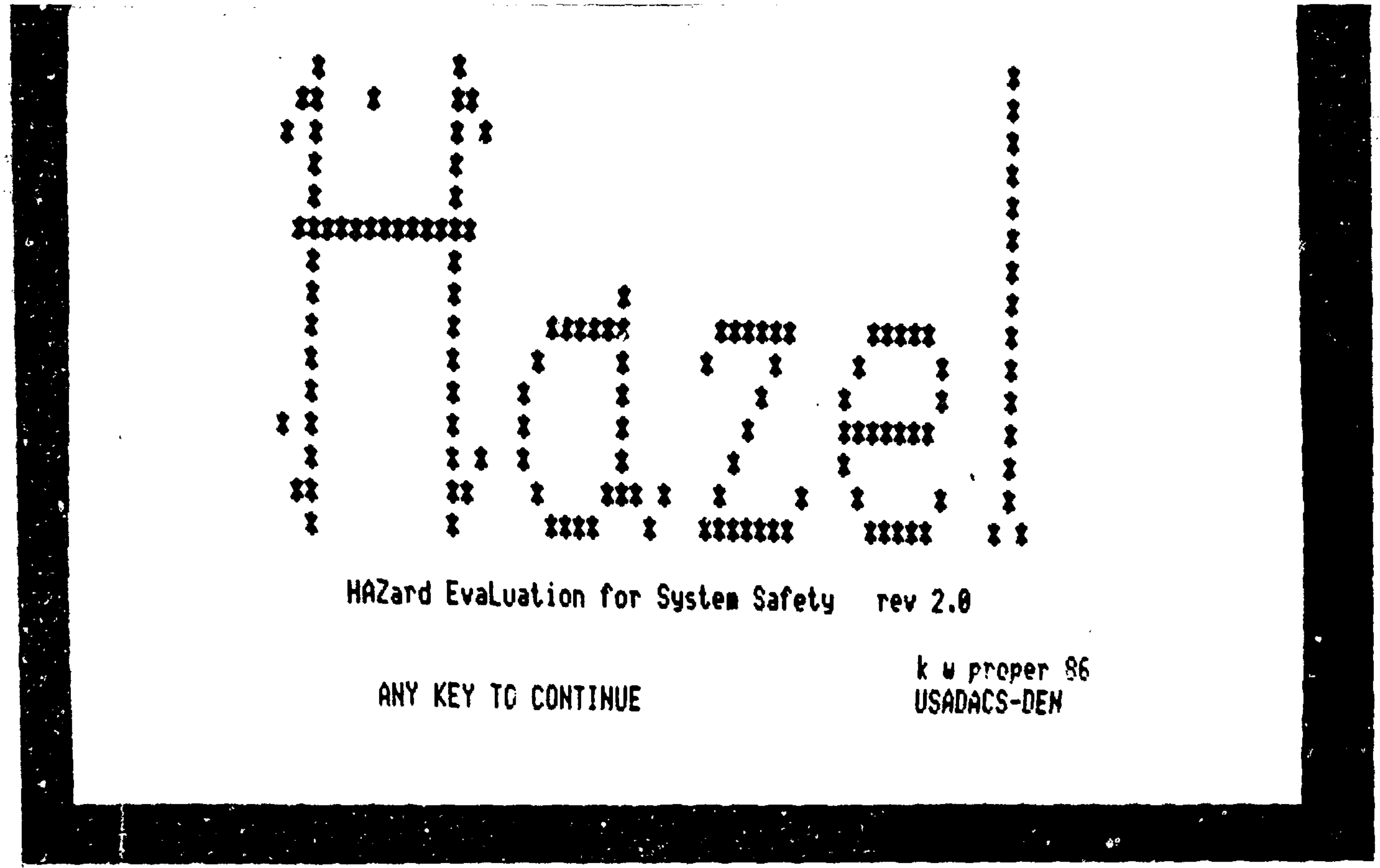
Final Usage: Fail Rate: R.F.: SEV: Criticality

Type Action: DESIGN ( ) SAFETY DEVICE ( ) WARNING DEVICE ( ) REDUNDACY ( )

RESULT: ELIMINATED ( ) REDUCED ( ) CONTROLLED ( ) TRADE-OFF ( )

APPENDIX D

SAMPLE MENUS AND PROGRAM FLOW



HAZard EvaLuation for System Safety rev 2.0

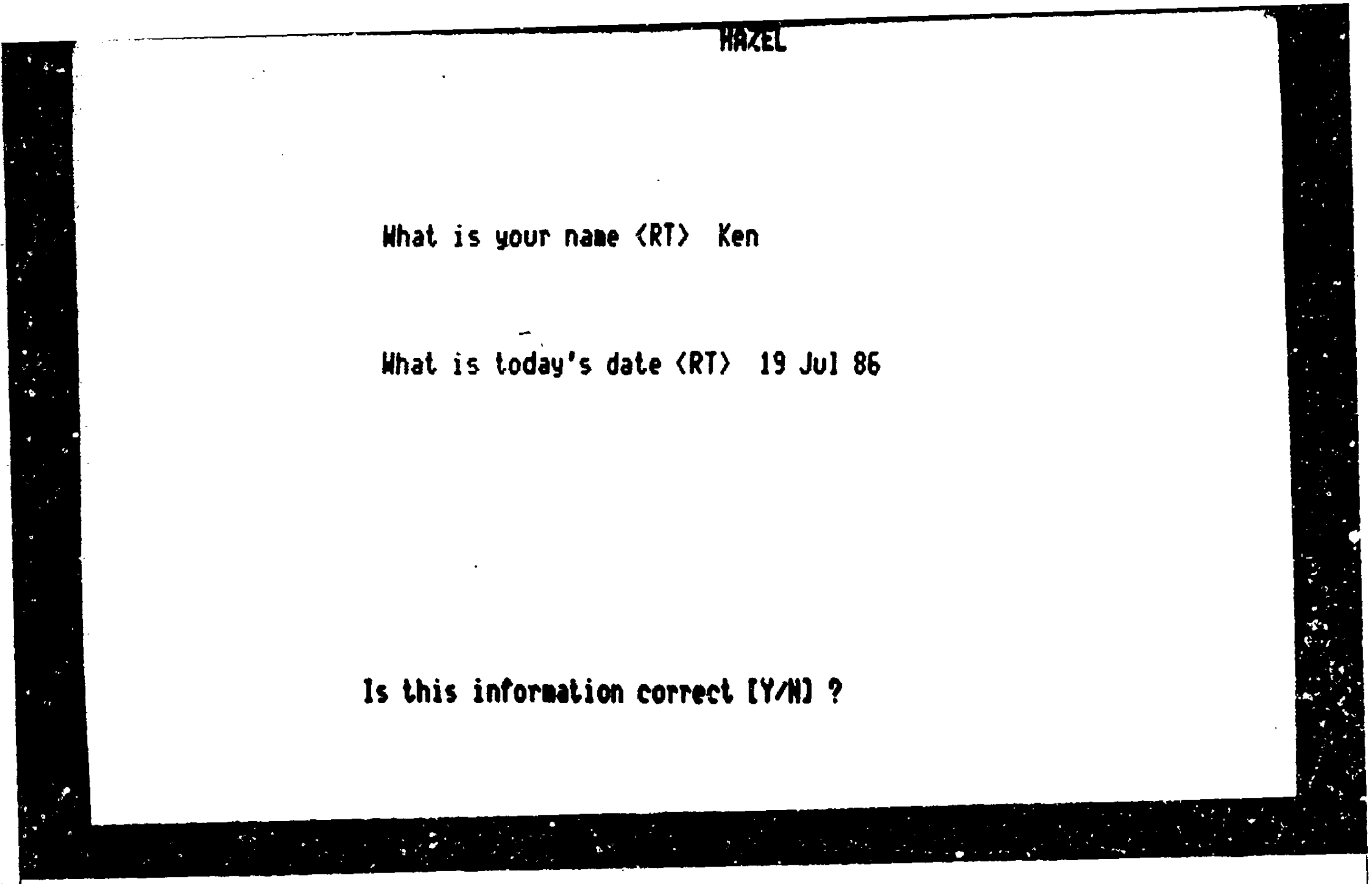
ANY KEY TO CONTINUE

k w proper 86
USADACS-DEN

OPENING SCREEN

This section contains sample menus, shows how HAZEL flows from one menu to another, and contains sample screens for starting a new file, the Preliminary Safety Analysis and Failure Modes and Effects Safety Analysis.

The opening screen is shown above. This screen appears when the program is first executed.



HAZEL

What is your name <RT> Ken

What is today's date <RT> 19 Jul 86

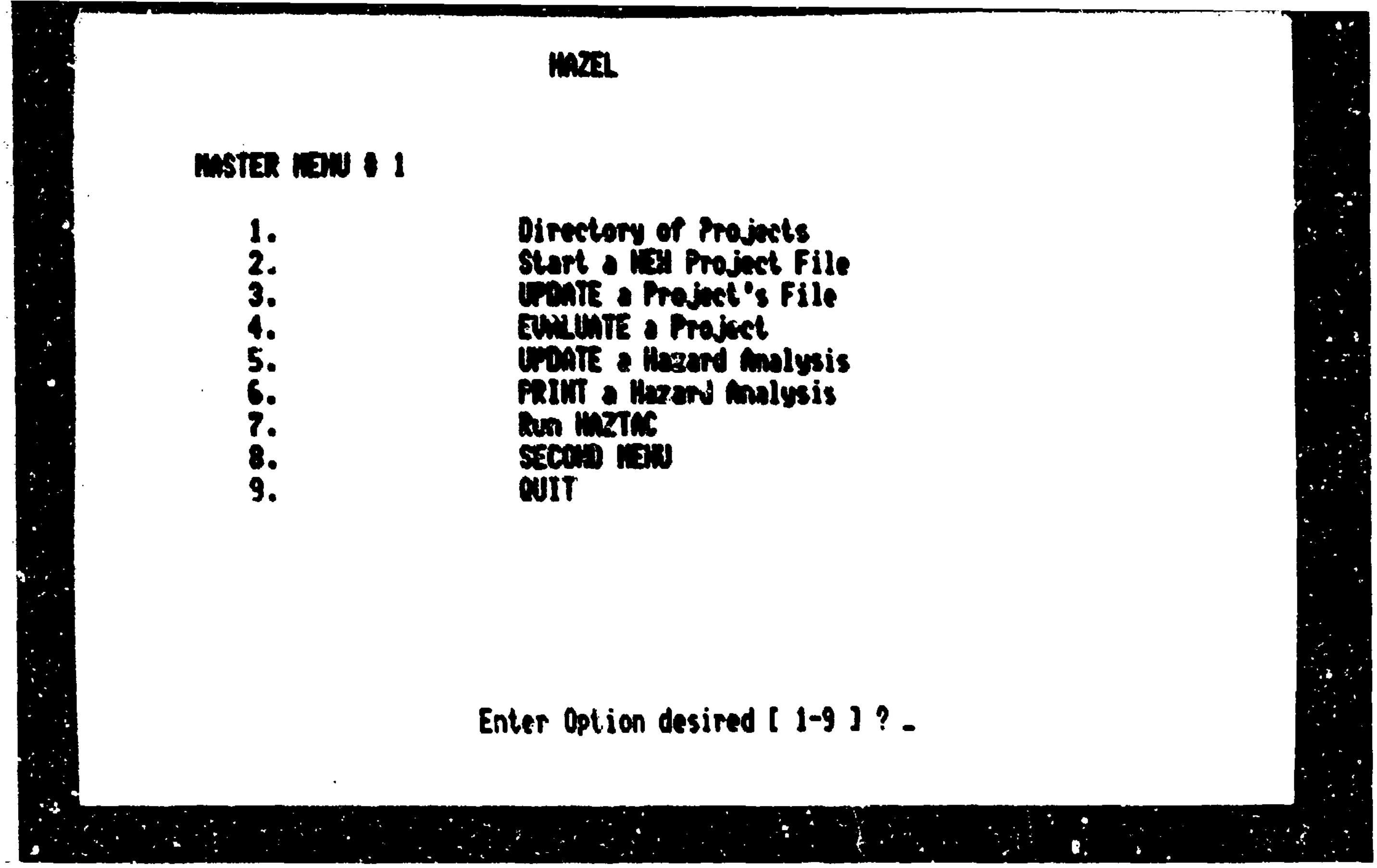
Is this information correct [Y/N] ?

NAME AND DATE SCREEN

The second screen shown above, requests that the name of the user and the current date be entered.

The current date is used for the opening date of the safety deficiencies determined, and, also, for the date printed on the different reports and analyses.

If the information is entered incorrectly, it can be reentered by answering "N" or "n" for the prompt.



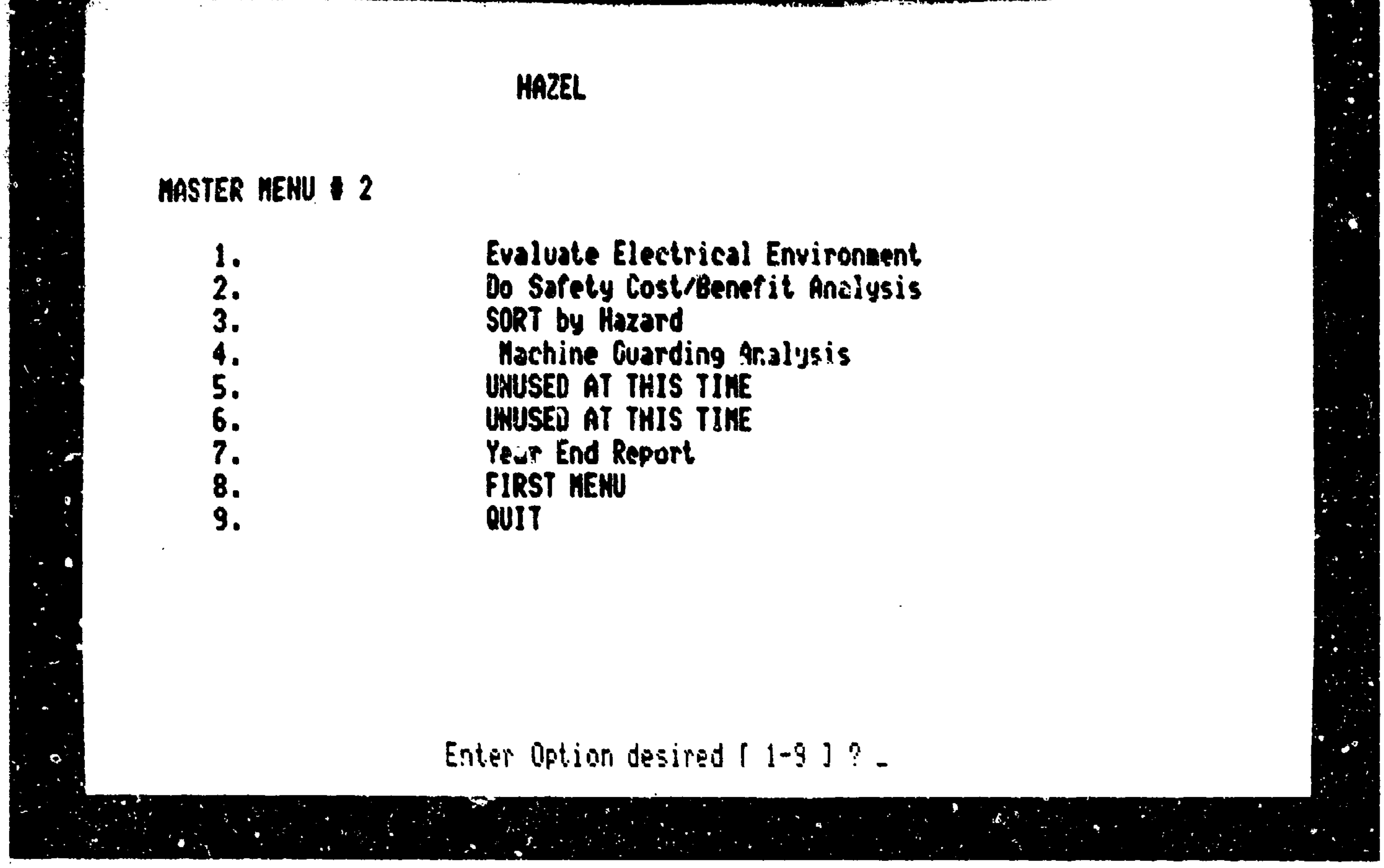
```
                              HAZEL

       MASTER MENU # 1

            1.                   Directory of Projects
            2.                   Start a NEW Project File
            3.                   UPDATE a Project's File
            4.                   EVALUATE a Project
            5.                   UPDATE a Hazard Analysis
            6.                   PRINT a Hazard Analysis
            7.                   Run HAZTAC
            8.                   SECOND MENU
            9.                   QUIT




                           Enter Option desired [ 1-9 ] ? _
```

MASTER MENU #1

This is the first master menu. HAZEL consists of two master menus at this time; however, more menus can be added to her to increase the tasks she can complete.

To go the second master menu, enter "8" as the option.

HAZEL will indicate the selection of "8" by placing stars between the "8" and "SECOND MENU"; and then asking if this is the correct option desired.

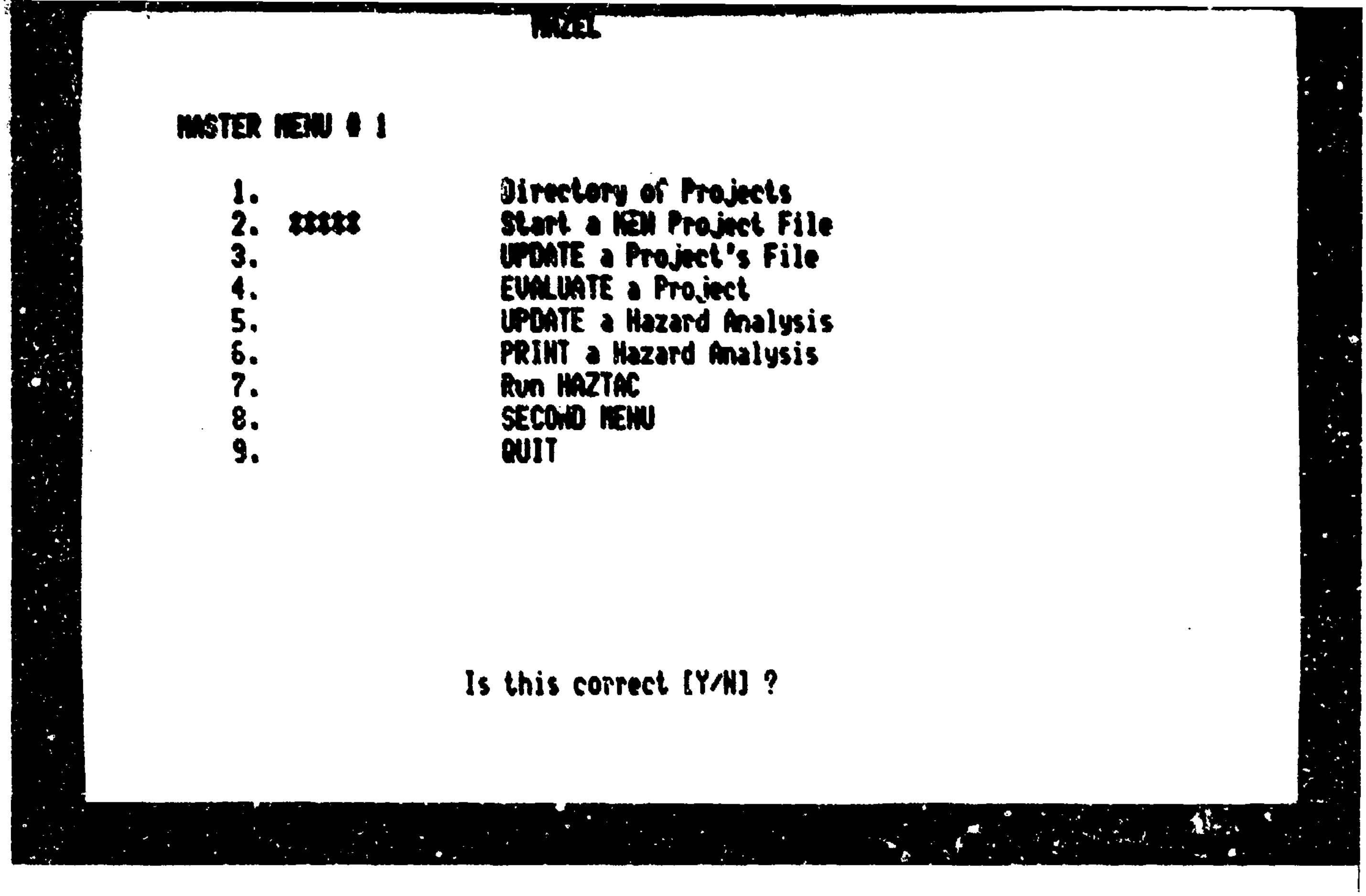


```
                    HAZEL

MASTER MENU # 2

   1.             Evaluate Electrical Environment
   2.             Do Safety Cost/Benefit Analysis
   3.             SORT by Hazard
   4.              Machine Guarding Analysis
   5.             UNUSED AT THIS TIME
   6.             UNUSED AT THIS TIME
   7.             Year End Report
   8.             FIRST MENU
   9.             QUIT




               Enter Option desired [ 1-9 ] ? _
```

MASTER MENU #2

This is the second master menu. Option 5 and 6 are unused at this time are available for future develoment.

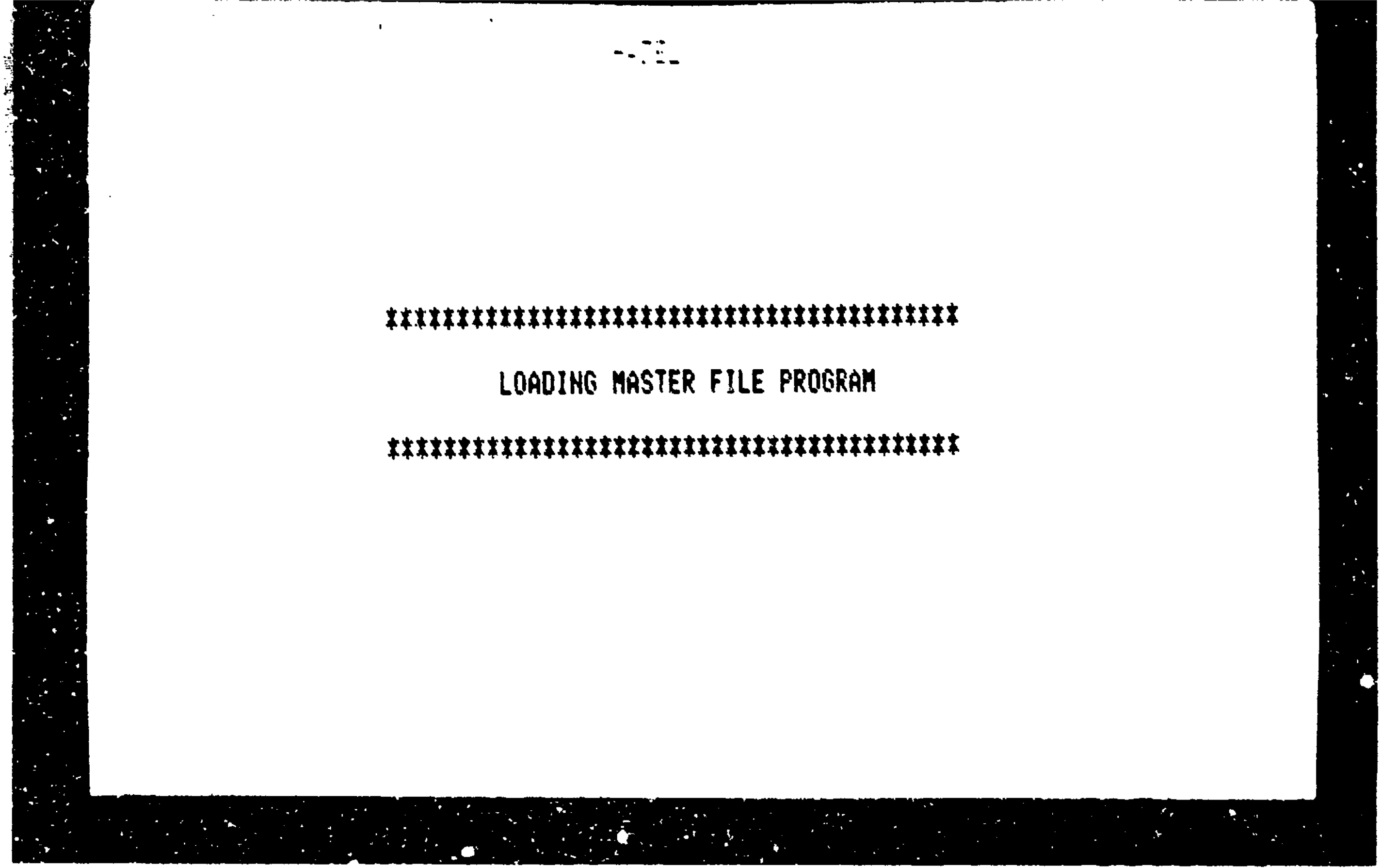
To return to the first master menu, enter "8" as the option.



```
                              HAZEL

      MASTER MENU # 1

            1.                    Directory of Projects
            2.  *****             Start a NEW Project File
            3.                    UPDATE a Project's File
            4.                    EVALUATE a Project
            5.                    UPDATE a Hazard Analysis
            6.                    PRINT a Hazard Analysis
            7.                    Run HAZTAC
            8.                    SECOND MENU
            9.                    QUIT




                         Is this correct [Y/N] ?
```

SELECTION OF "START A NEW PROJECT FILE" OPTION

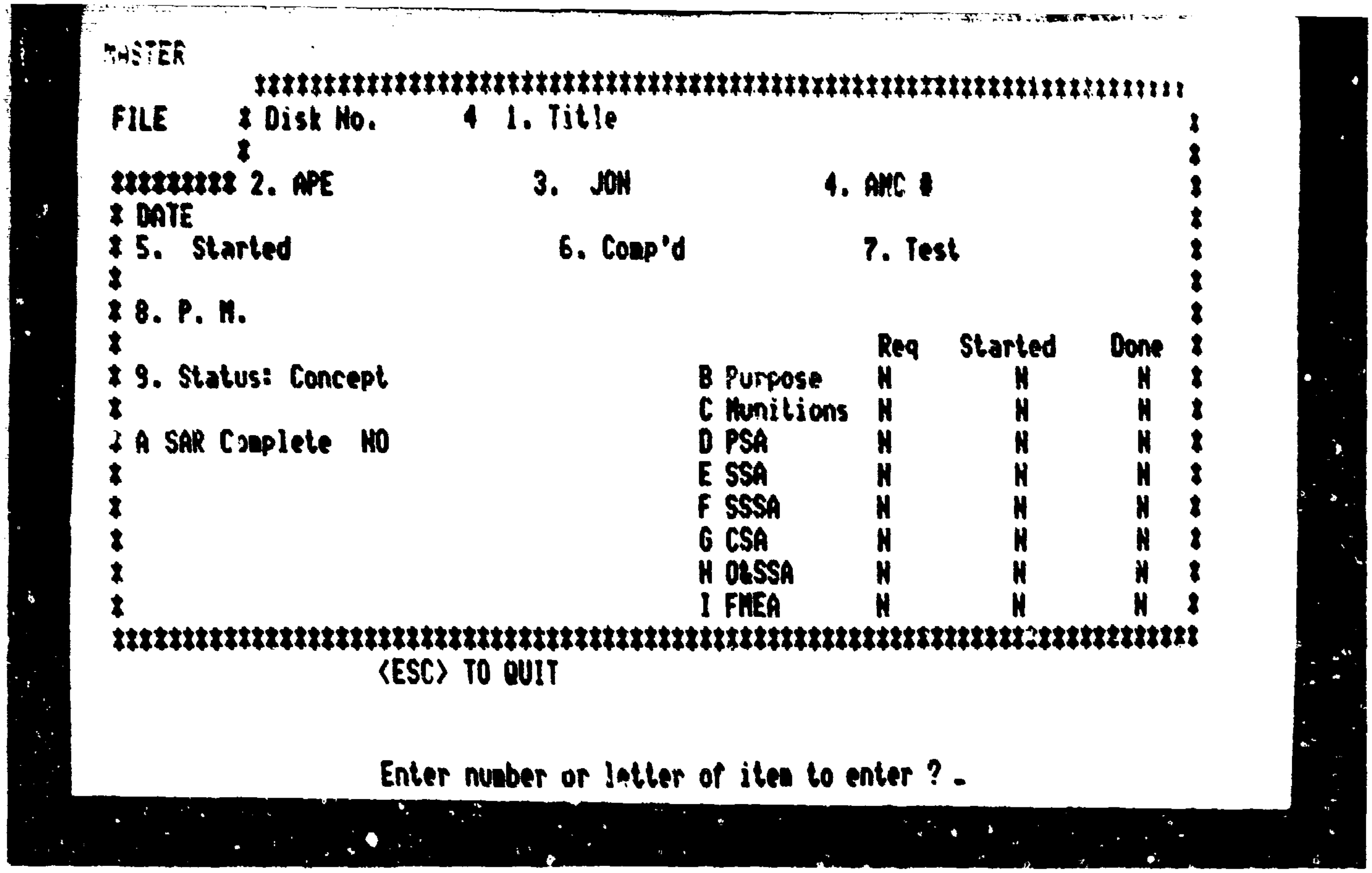
When the system safety for a project is first begun, a master file for that project must be established. This is accomplished using option 2 of Master Menu #1.



```
*****************************************

        LOADING MASTER FILE PROGRAM

*****************************************
```

TRANSITION SCREEN

The above screen is typical of the type of screen which appears when HAZEL is moving from one program to another.

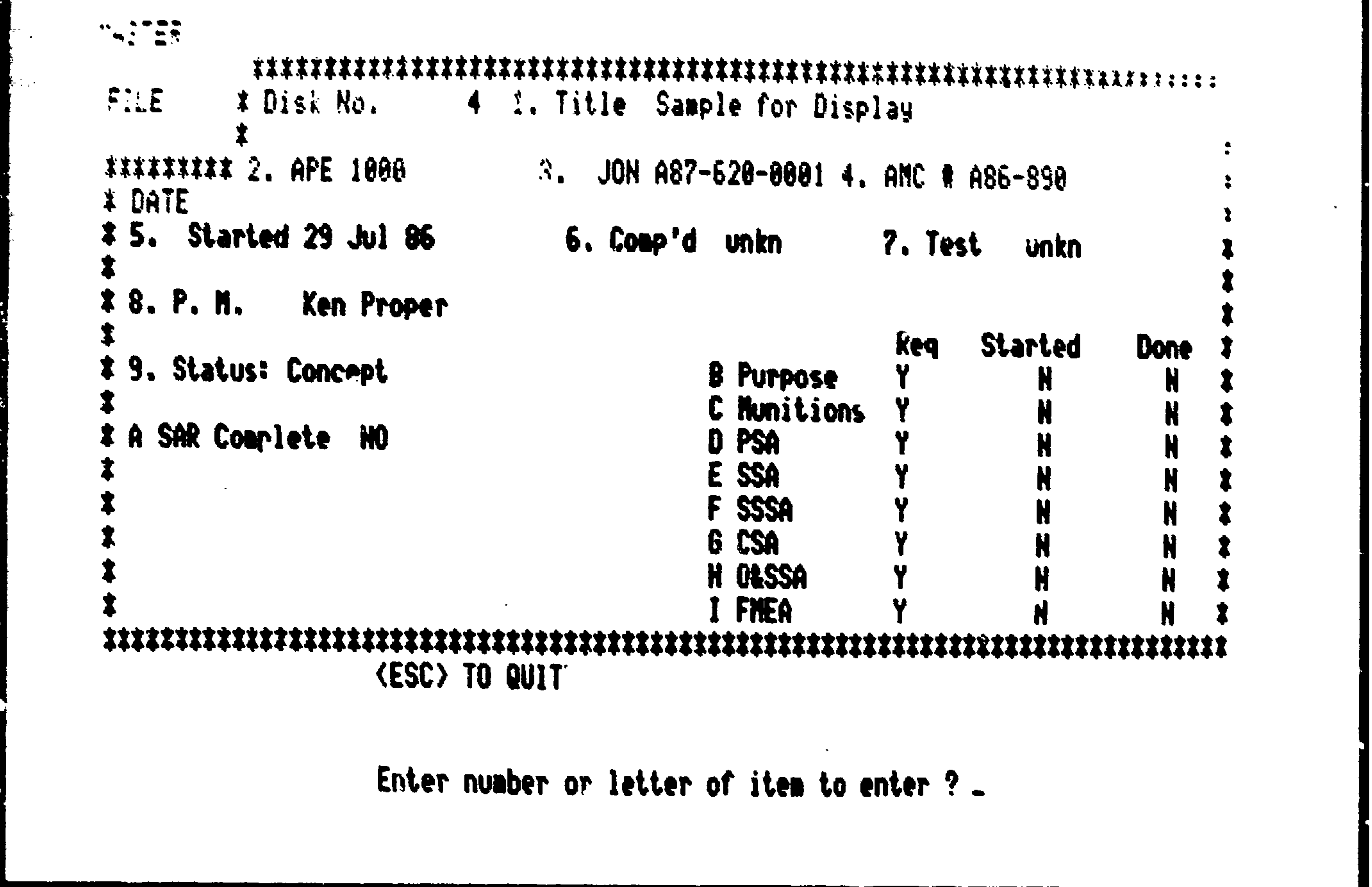


```
MASTER
           ****************************************************************
FILE     * Disk No.     4  1. Title                                       *
           *                                                              *
********* 2. APE              3.  JON            4. AMC #                  *
* DATE                                                                    *
* 5.  Started                 6. Comp'd           7. Test                 *
*                                                                         *
* 8. P. M.                                                                *
*                                                   Req   Started   Done  *
* 9. Status: Concept                  B Purpose     N        N        N   *
*                                     C Munitions   N        N        N   *
* A SAR Complete  NO                  D PSA         N        N        N   *
*                                     E SSA         N        N        N   *
*                                     F SSSA        N        N        N   *
*                                     G CSA         N        N        N   *
*                                     H O&SSA       N        N        N   *
*                                     I FMEA        N        N        N   *
***************************************************************************
                  <ESC> TO QUIT

                  Enter number or letter of item to enter ? _
```

MASTER FILE SCREEN

This is the screen which will appear when a new project is being added to the file.

Each item can be entered by indicating the number or letter for that item. Each item can be entered as many times as desired, until the file data is correct.



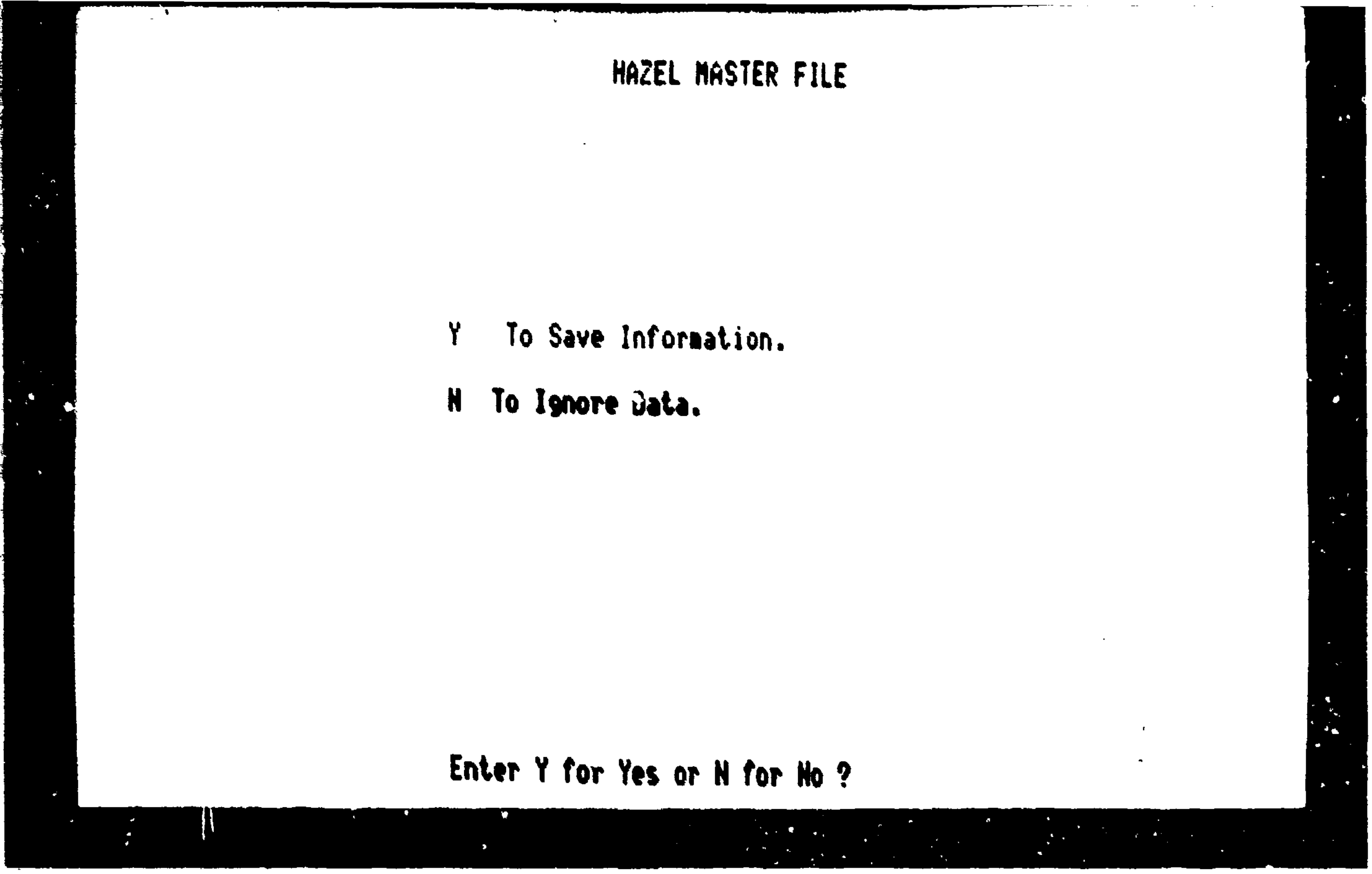
```
MASTER
        ****************************************************************::::
FILE    * Disk No.     4  1. Title  Sample for Display
        *                                                                   :
********* 2. APE 1000          3.  JON A87-620-0001 4. AMC # A86-890        :
* DATE                                                                      :
* 5.  Started 29 Jul 86        6. Comp'd  unkn       7. Test   unkn         *
*                                                                           *
* 8. P. M.    Ken Proper                                                    *
*                                                  Req    Started    Done   *
* 9. Status: Concept                  B Purpose    Y         N         N    *
*                                     C Munitions  Y         N         N    *
* A SAR Complete  NO                  D PSA        Y         N         N    *
*                                     E SSA        Y         N         N    *
*                                     F SSSA       Y         N         N    *
*                                     G CSA        Y         N         N    *
*                                     H O&SSA      Y         N         N    *
*                                     I FMEA       Y         N         N    *
*****************************************************************************
                  <ESC> TO QUIT


                  Enter number or letter of item to enter ? _
```

COMPLETED MASTER FILE SCREEN

This is a sample of a completed Master File Screen.

This is, also, the same screen which would appear if the file was being updated, using option 3 of Master Menu #1.

Once the information is correct, use the "ESCAPE" key to go to the next screen.



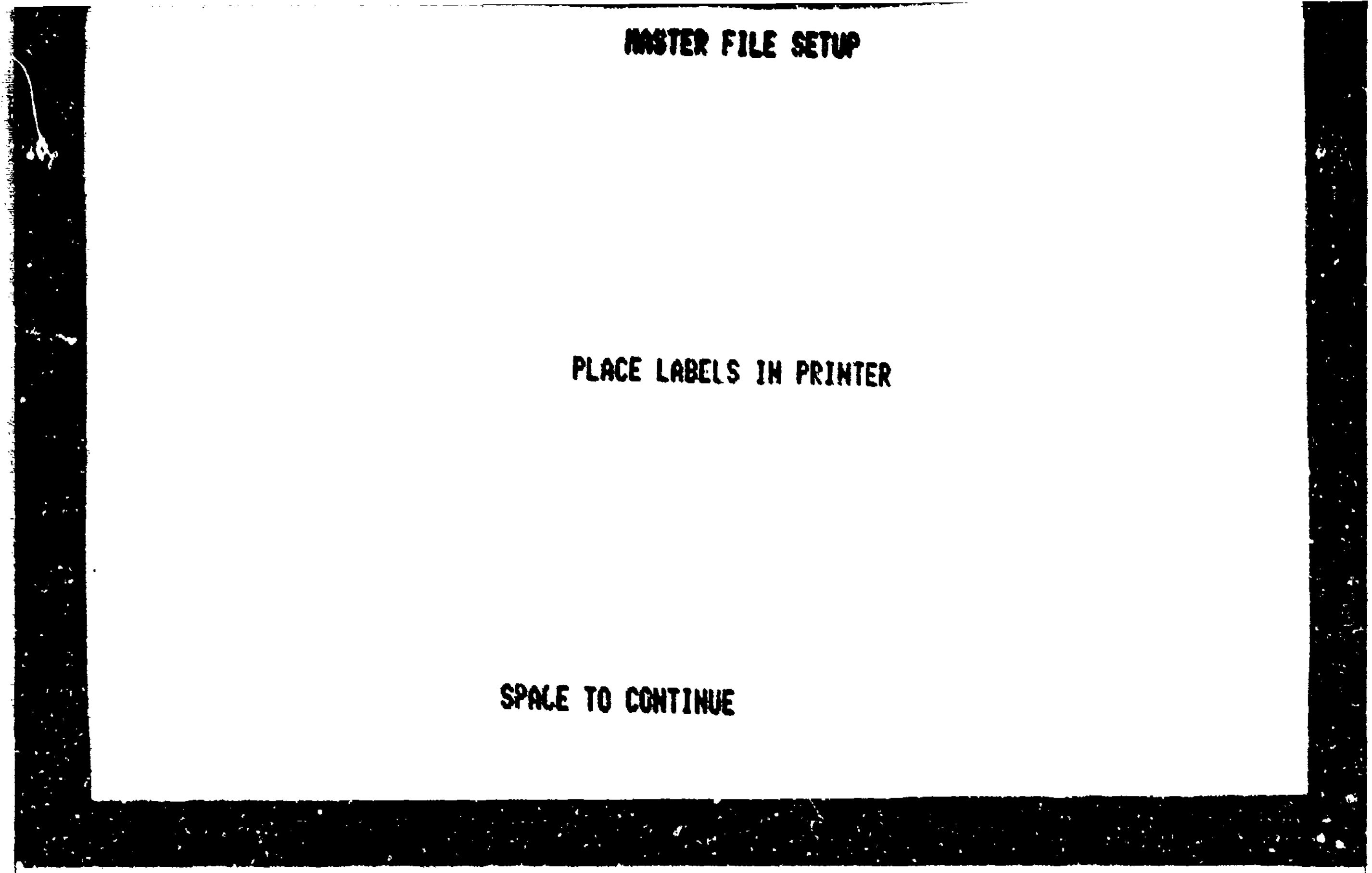
```
HAZEL MASTER FILE

Y   To Save Information.

N  To Ignore Data.

Enter Y for Yes or N for No ?
```

MASTER FILE SAVE SCREEN

This screen allows the data entered to be saved or not.

If the new or changed data is not to be saved, entering "N" will cause HAZEL to return to Master Menu #1.

If the Update File option were used, the changed data would be saved and printed, and then HAZEL will return to Master Menu #1.



MASTER FILE SETUP

PLACE LABELS IN PRINTER

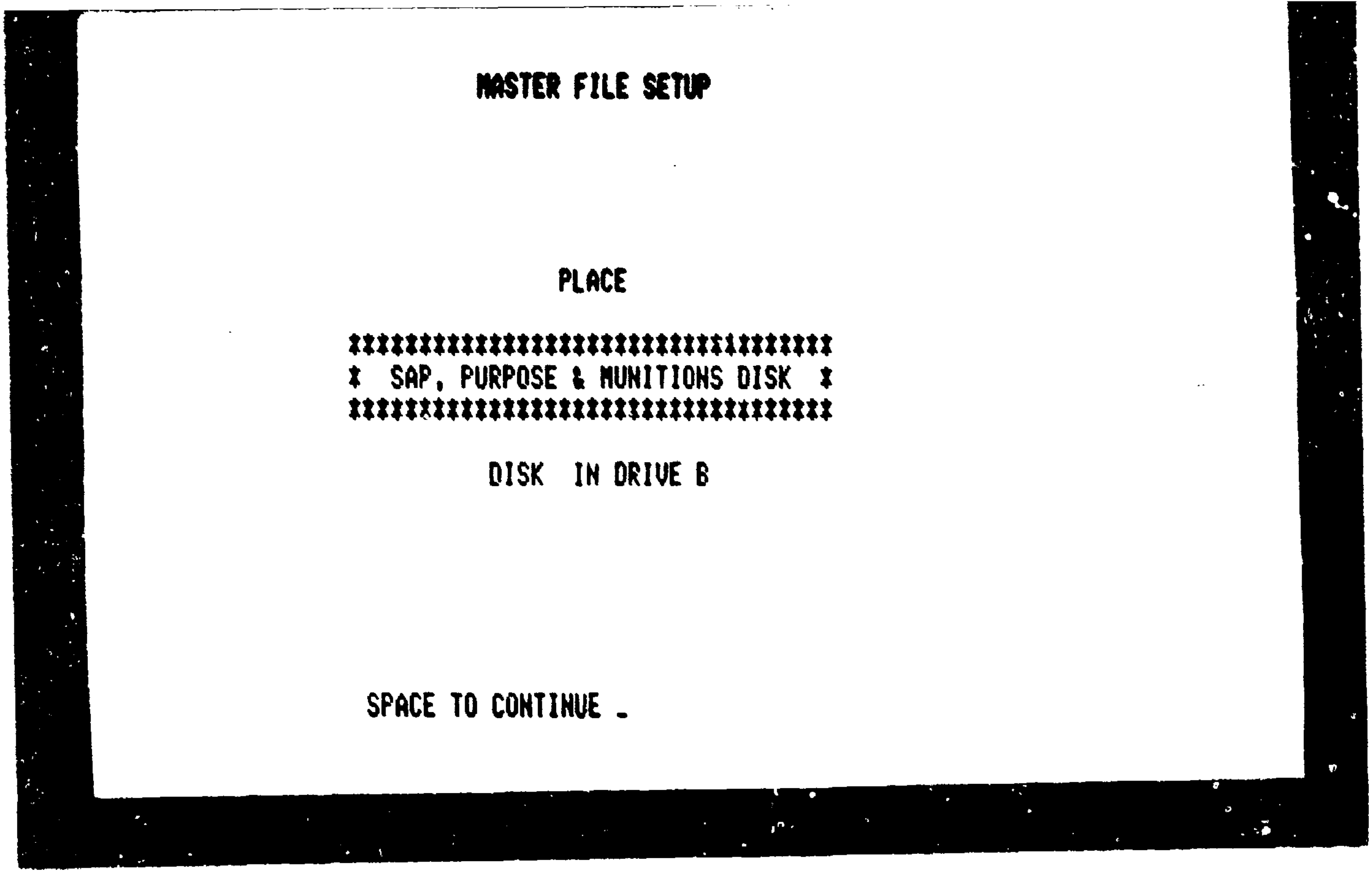
SPACE TO CONTINUE

MASTER FILE SETUP SCREEN #2

This is the next screen which would appear when starting a new project file.

Once the labels have been placed in the printer, the pressing of the space bar will cause them to be printed.

Ten labels will be produced.

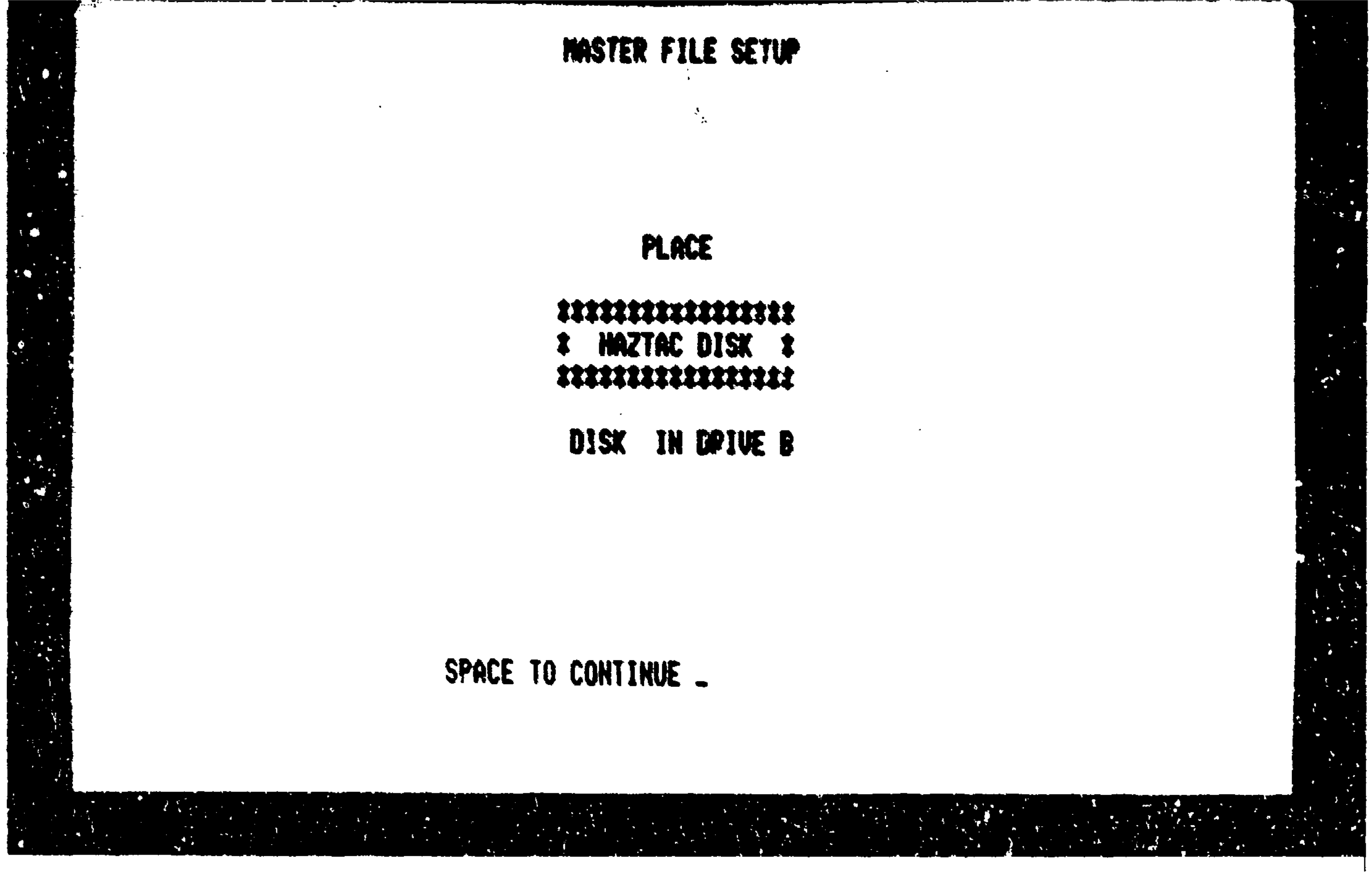


```
                MASTER FILE SETUP



                     PLACE

         ************************************
         *  SAP, PURPOSE & MUNITIONS DISK  *
         ************************************

                DISK  IN DRIVE B




         SPACE TO CONTINUE _
```

MASTER FILE SETUP SCREEN #3

Using this screen, HAZEL calls for a formatted disk to be placed in Drive B.

Once the disk has been inserted and the space bar pressed, HAZEL will create and write master files on this disk.



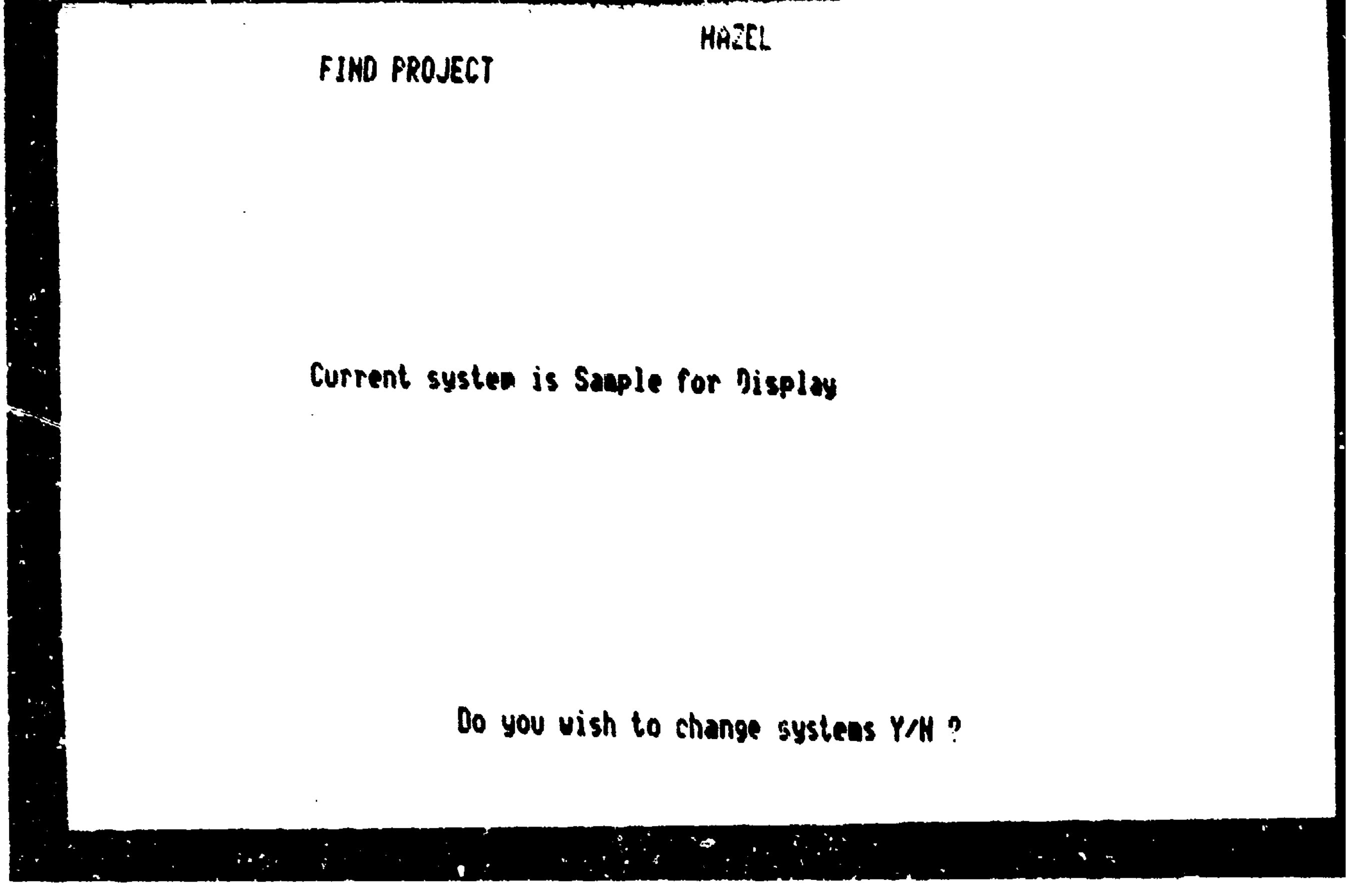
```
MASTER FILE SETUP



PLACE

*****************
* HAZTAC DISK  *
*****************

DISK  IN DRIVE B




SPACE TO CONTINUE _
```

MASTER FILE SETUP SCREEN #4

Using this screen, HAZEL calls for a formatted disk to be placed in Drive B.

Once the disk has been inserted and the space bar pressed, HAZEL will create and write the files necessary for tracking all safety deficiencies found by the safety evaluations completed.

After this has been completed, HAZEL will return to Master Menu #1.



HAZEL

FIND PROJECT

Current system is Sample for Display

Do you wish to change systems Y/N ?

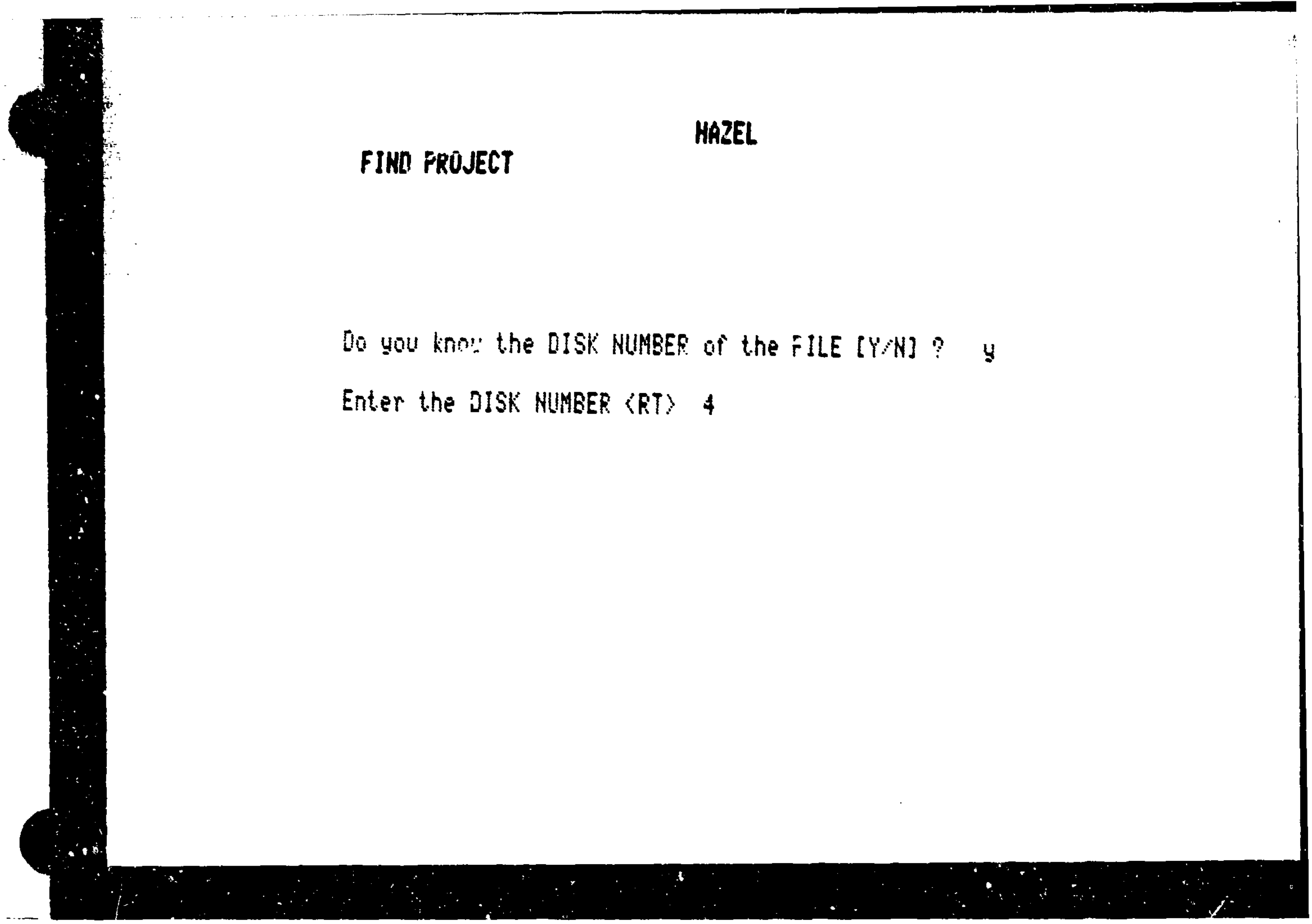
FIND PROJECT SCREEN #1

Whenever any option selected on either menu involves the evaluation, updating or printing of a project, the above screen appears.

This screen allows changing from one project to another without having to re-load HAZEL.

If it is wished to continue with the current system or project then "N" or "n" is entered; and HAZEL will continue with the option selected.

If it is wished to change systems then either a "Y" or "y" is entered; and then HAZEL will present Find Project Screen #2.



```
                         HAZEL
   FIND PROJECT



      Do you know the DISK NUMBER of the FILE [Y/N] ?   y

      Enter the DISK NUMBER <RT>  4
```

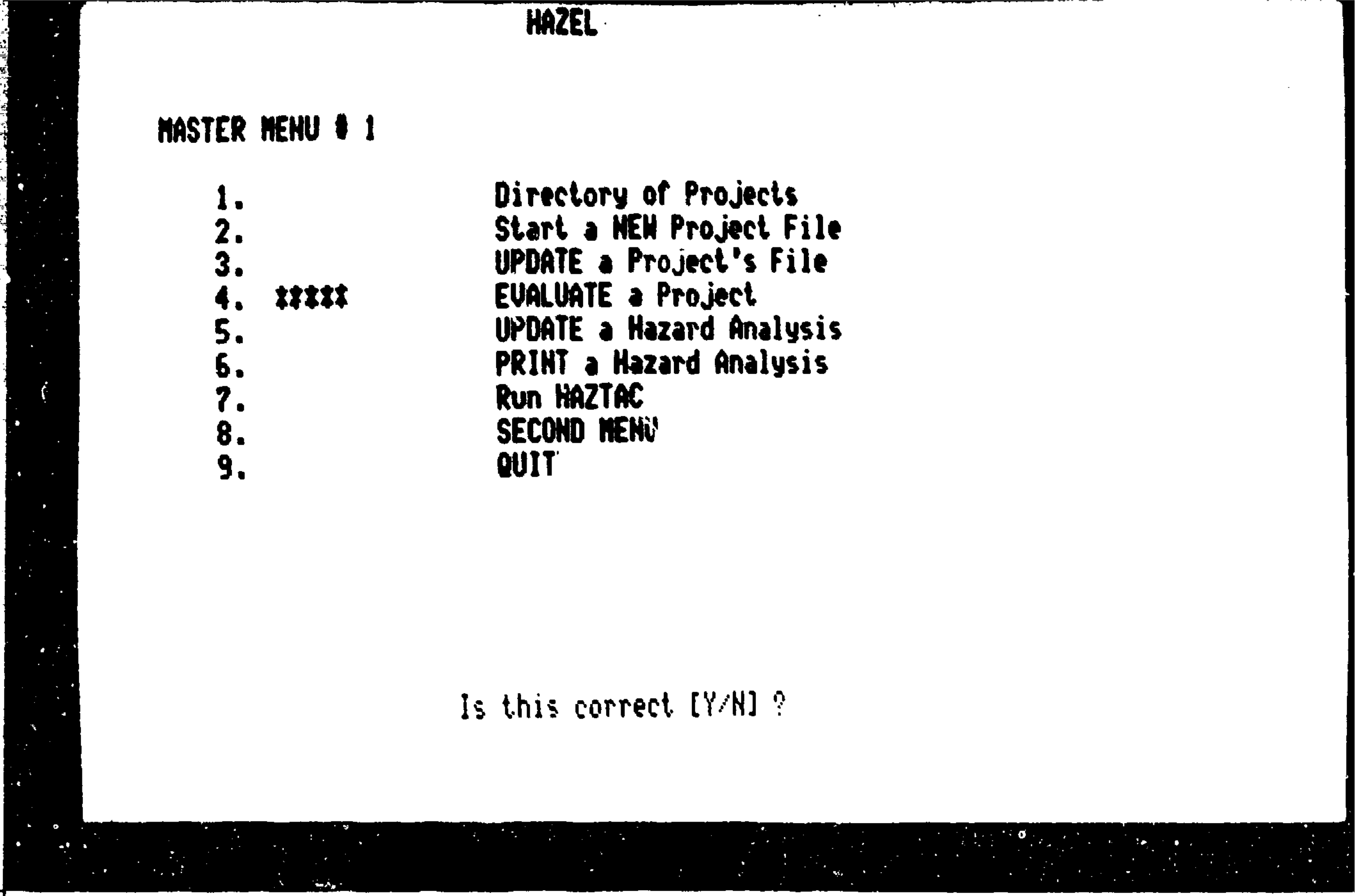
FIND PROJECT SCREEN #2

HAZEL will ask if the Disk Number for the system is known.

If not, HAZEL will request the Directory option be used to find it and return to Master Menu #1.

If it is known, HAZEL will ask for it to be entered.

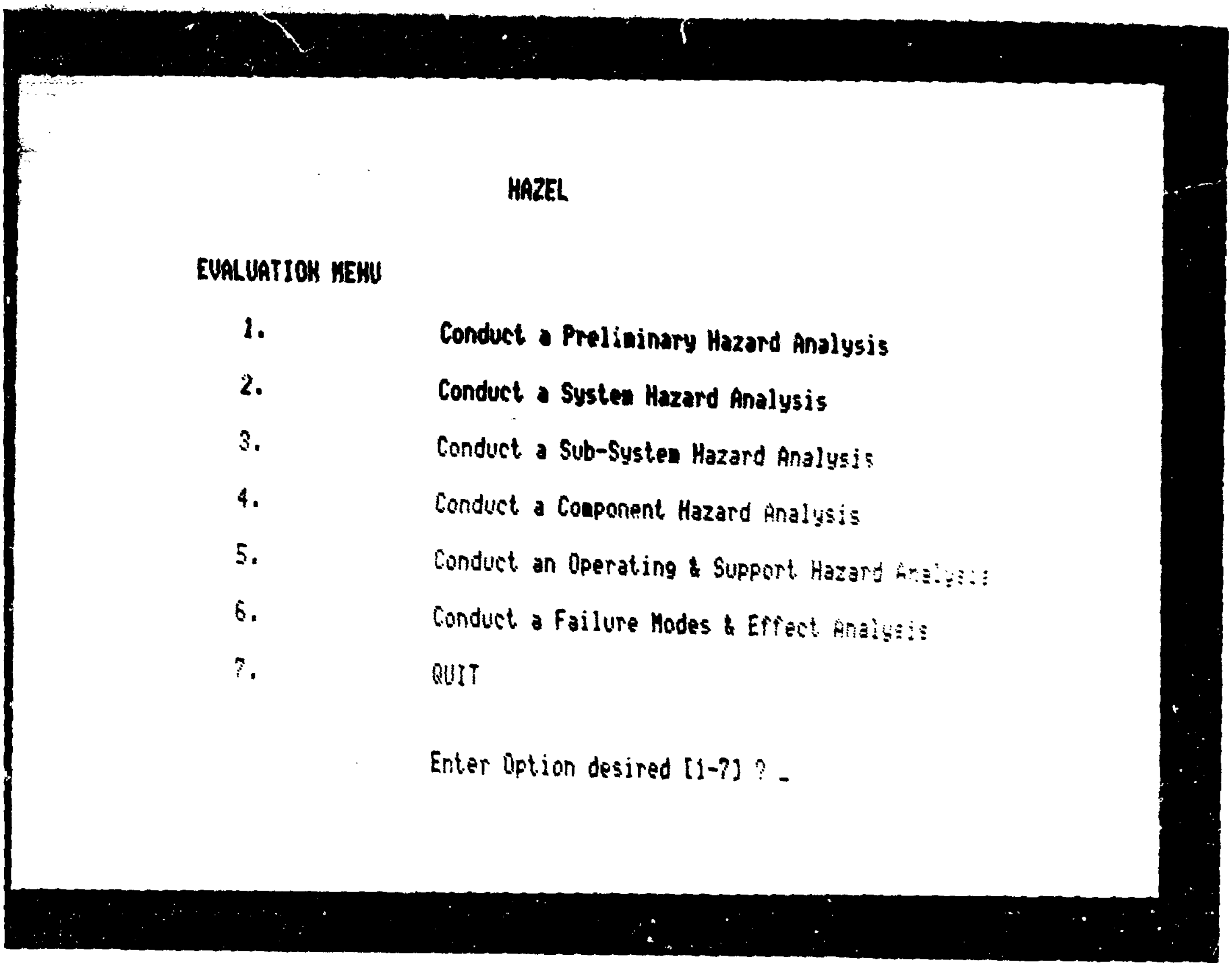
Then HAZEL will show the name of the project and ask if it is correct. If correct, HAZEL will then load the option requested.



```
                        HAZEL

MASTER MENU # 1

     1.                 Directory of Projects
     2.                 Start a NEW Project File
     3.                 UPDATE a Project's File
     4.  *****          EVALUATE a Project
     5.                 UPDATE a Hazard Analysis
     6.                 PRINT a Hazard Analysis
     7.                 Run HAZTAC
     8.                 SECOND MENU
     9.                 QUIT



                  Is this correct [Y/N] ?
```

EVALUATION PROCESS

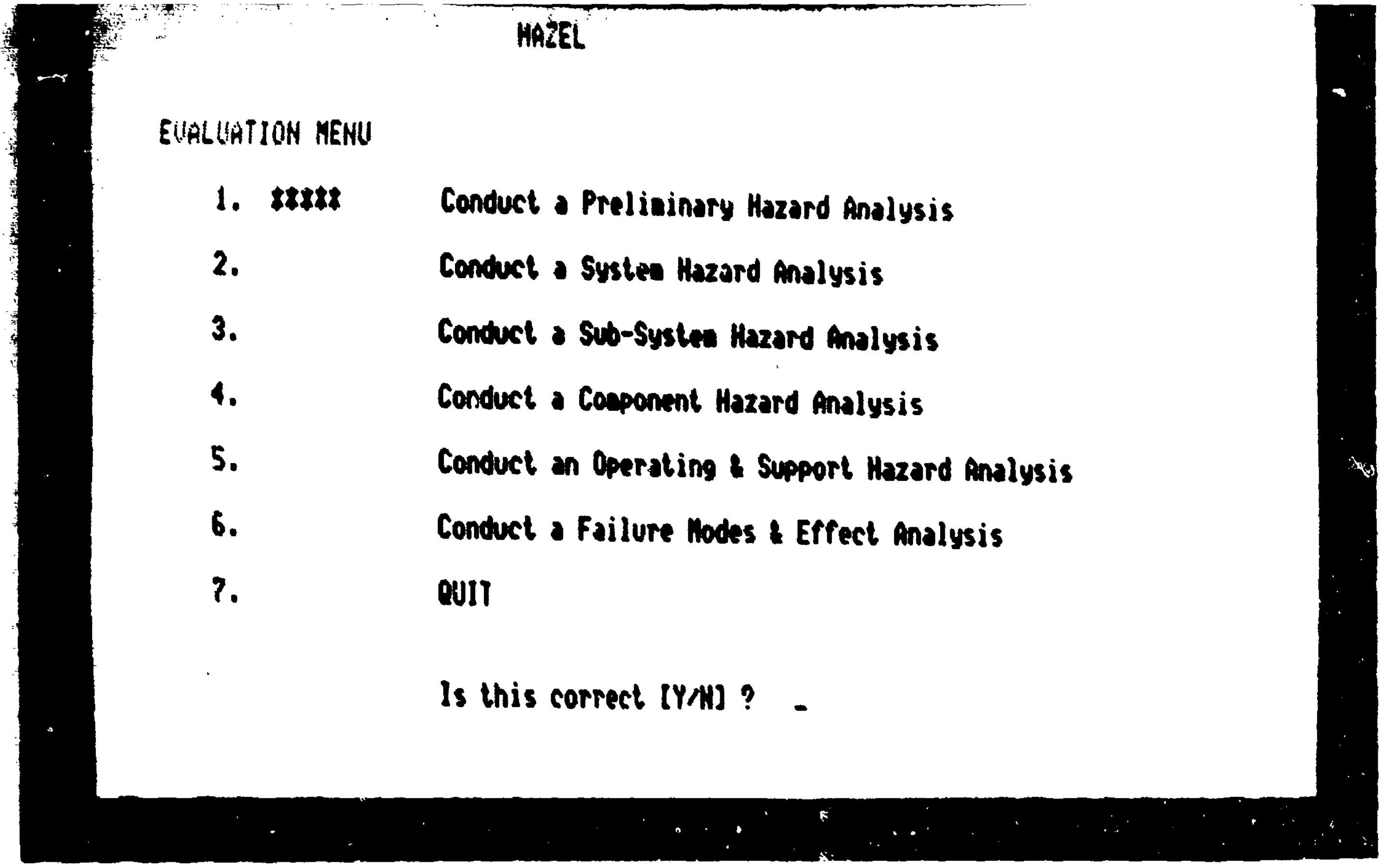
The following screens and menus will show the process of evaluating, updating and printing for two types of Safety Analysis - Preliminary and FMEA.



```
                        HAZEL

EVALUATION MENU

     1.          Conduct a Preliminary Hazard Analysis

     2.          Conduct a System Hazard Analysis

     3.          Conduct a Sub-System Hazard Analysis

     4.          Conduct a Component Hazard Analysis

     5.          Conduct an Operating & Support Hazard Analysis

     6.          Conduct a Failure Modes & Effect Analysis

     7.          QUIT

                 Enter Option desired [1-7] ? _
```

EVALUATION MENU

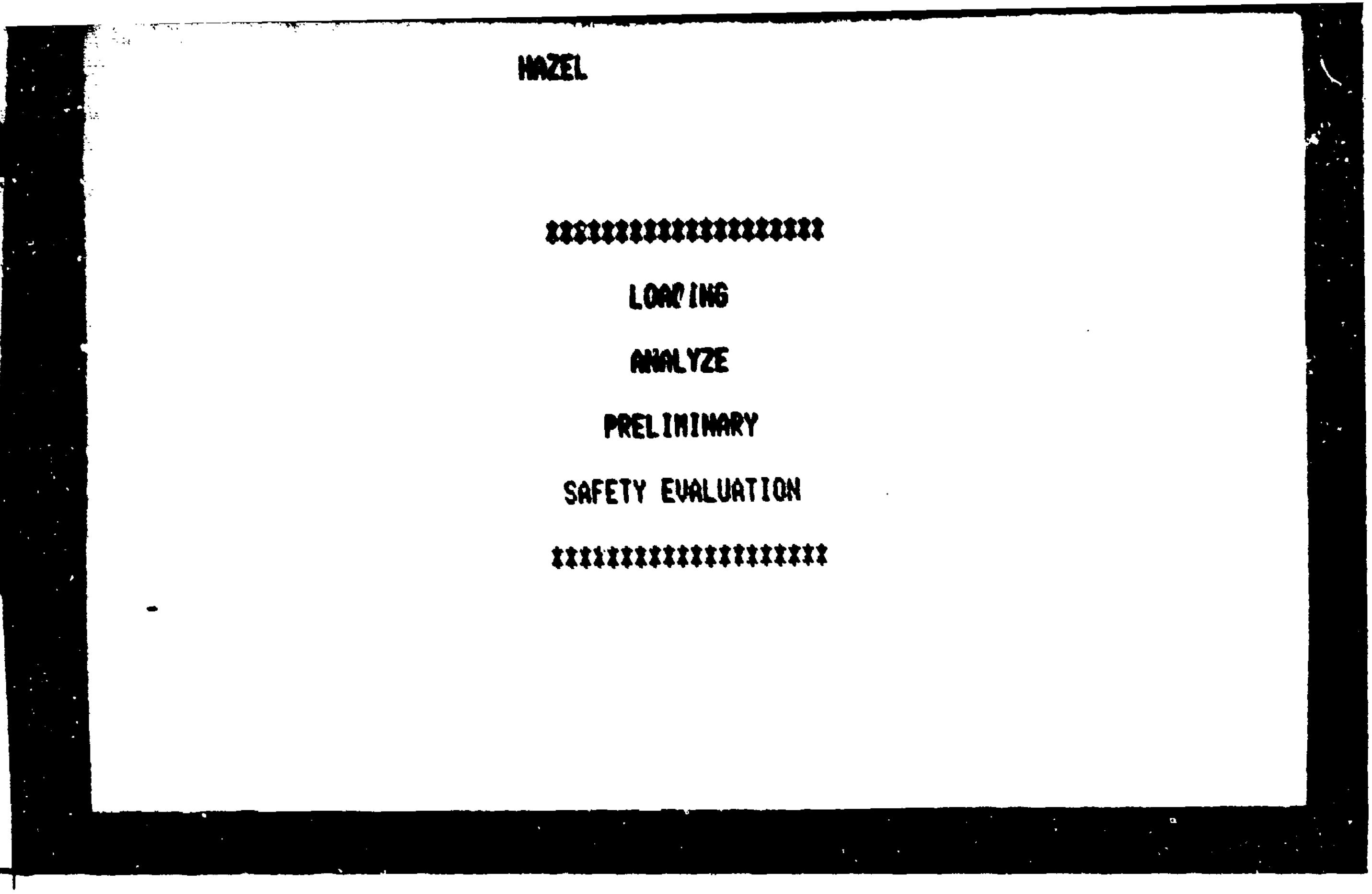
This menu allows selection of the type of evaluation to be conducted.



```
                         HAZEL

EVALUATION MENU

    1.  *****     Conduct a Preliminary Hazard Analysis

    2.            Conduct a System Hazard Analysis

    3.            Conduct a Sub-System Hazard Analysis

    4.            Conduct a Component Hazard Analysis

    5.            Conduct an Operating & Support Hazard Analysis

    6.            Conduct a Failure Modes & Effect Analysis

    7.            QUIT


                  Is this correct [Y/N] ?  _
```

SELECTION OF EVALUATION

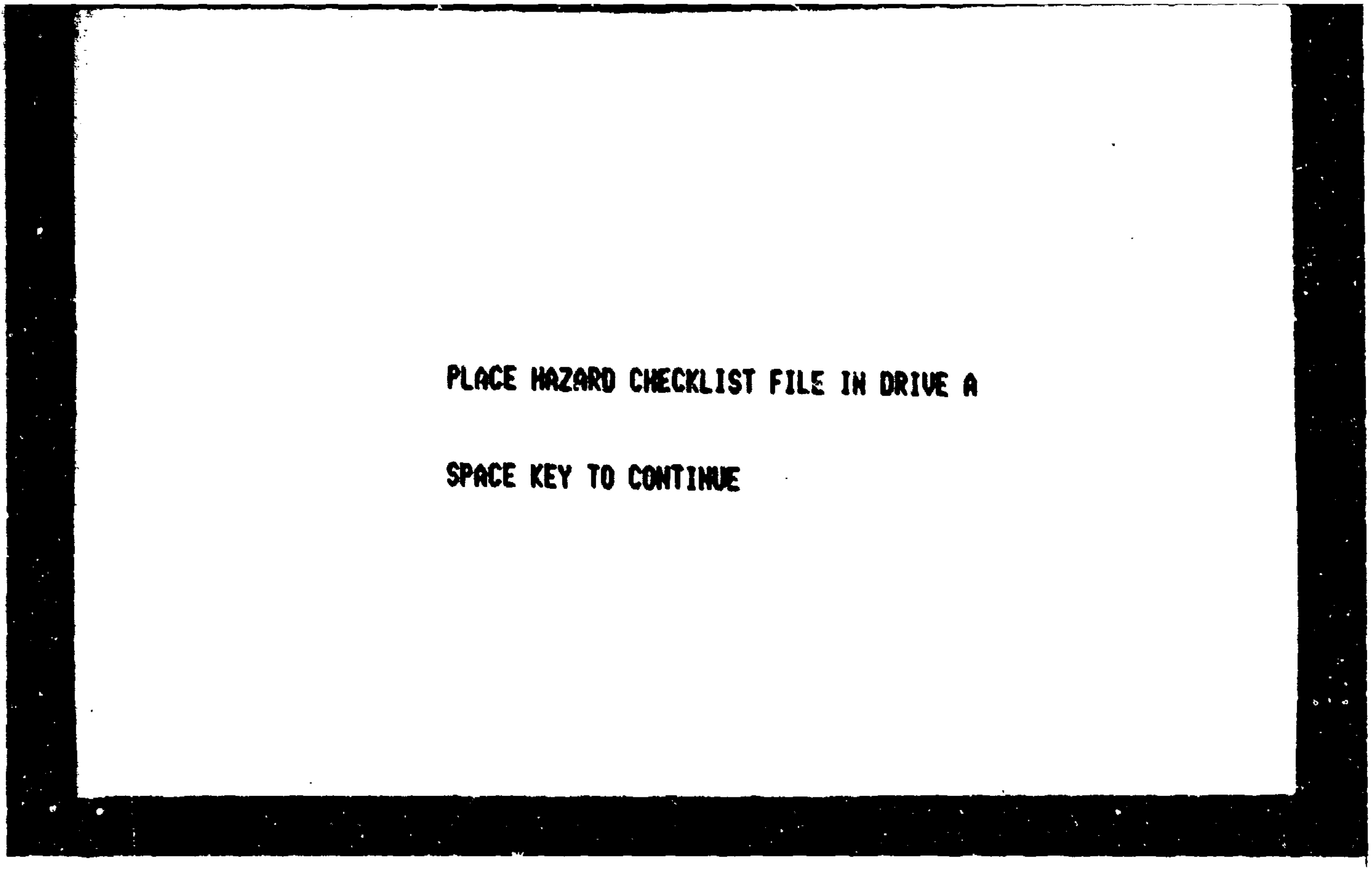
Here the stars between "1" and "Conduct a Preliminary Hazard Analysis" indicate this option was selected.



```
HAZEL

********************

LOADING

ANALYZE

PRELIMINARY

SAFETY EVALUATION

********************
```

CHANGING PROGRAM SCREEN

This screen indicates HAZEL is loading a new program.



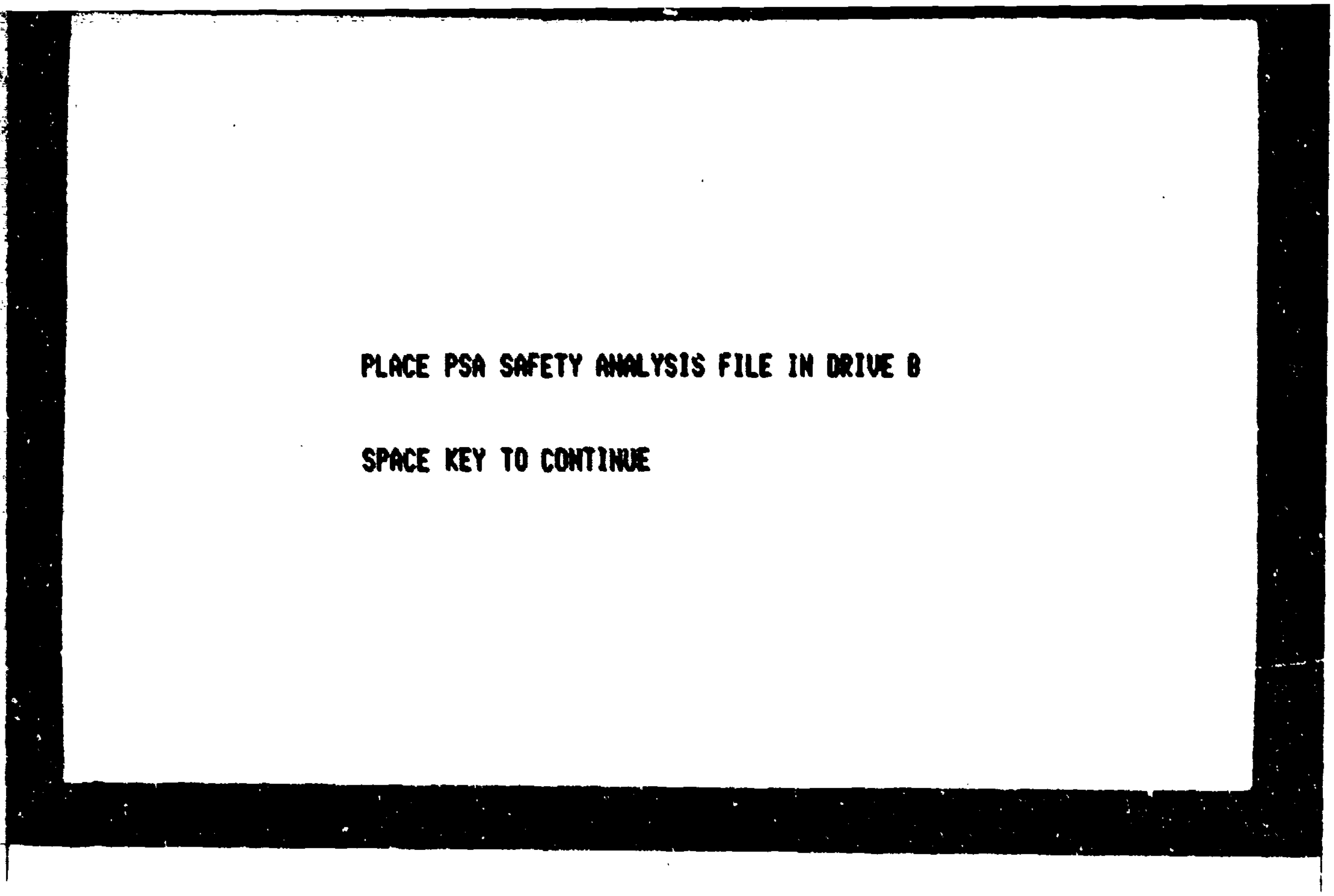
PLACE HAZARD CHECKLIST FILE IN DRIVE A

SPACE KEY TO CONTINUE

LOAD HAZARD CHECKLIST FILE SCREEN

HAZEL is requesting the Hazard Checklist File be placed in Drive A.

She will check to be sure the correct disk was placed in Drive A before continuing.



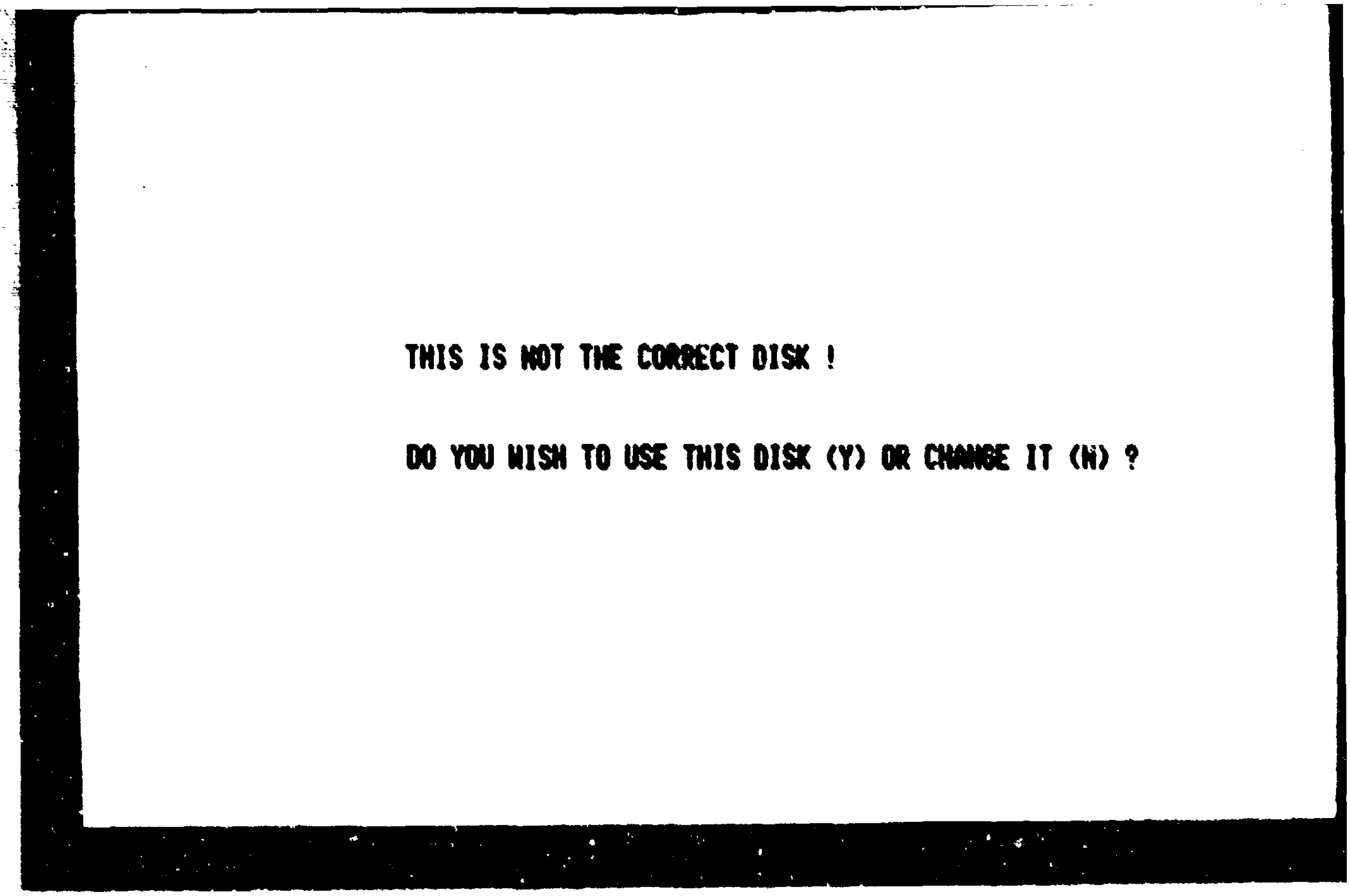
PLACE PSA SAFETY ANALYSIS FILE IN DRIVE B

SPACE KEY TO CONTINUE

LOAD PSA DISK SCREEN

HAZEL will then request the PSA disk to be placed in Drive B.

She will check to see the correct disk is placed in Drive B before continuing.



THIS IS NOT THE CORRECT DISK !

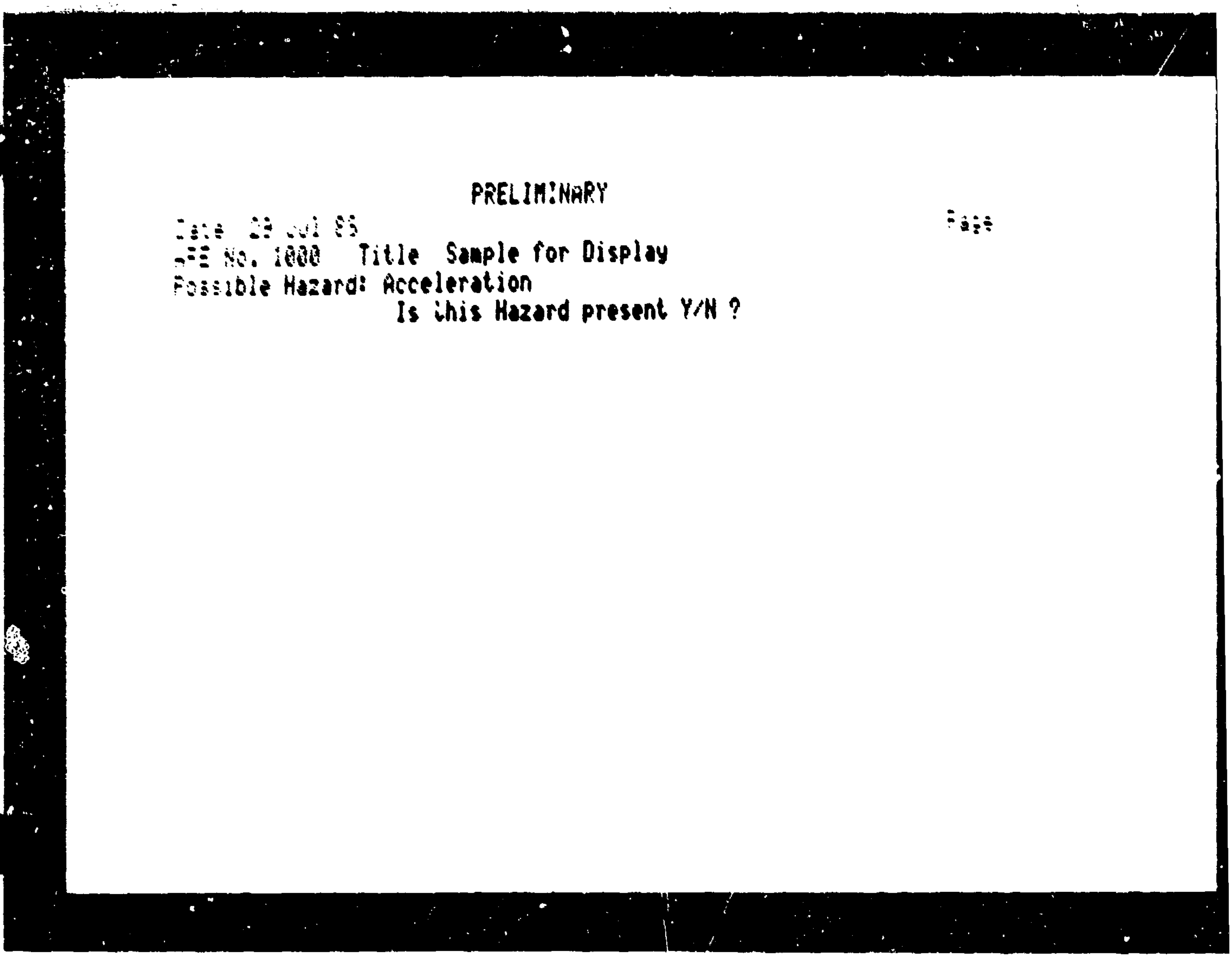
DO YOU WISH TO USE THIS DISK (Y) OR CHANGE IT (N) ?

WRONG DISK SCREEN

Since the PSA disk has never been used and the disk in Drive B is a blank, formatted disk, HAZEL is asking if this is the disk to be used in the future for PSA.

If the answer is yes, then HAZEL will setup the correct files and continue.

If the answer is no, then HAZEL will wait for the disk to be changed and rechecked until the correct disk is in place.



```
                          PRELIMINARY
Date  29 Jul 85                                                Page
PFE No. 1000   Title  Sample for Display
Possible Hazard: Acceleration
                     Is this Hazard present Y/N ?
```

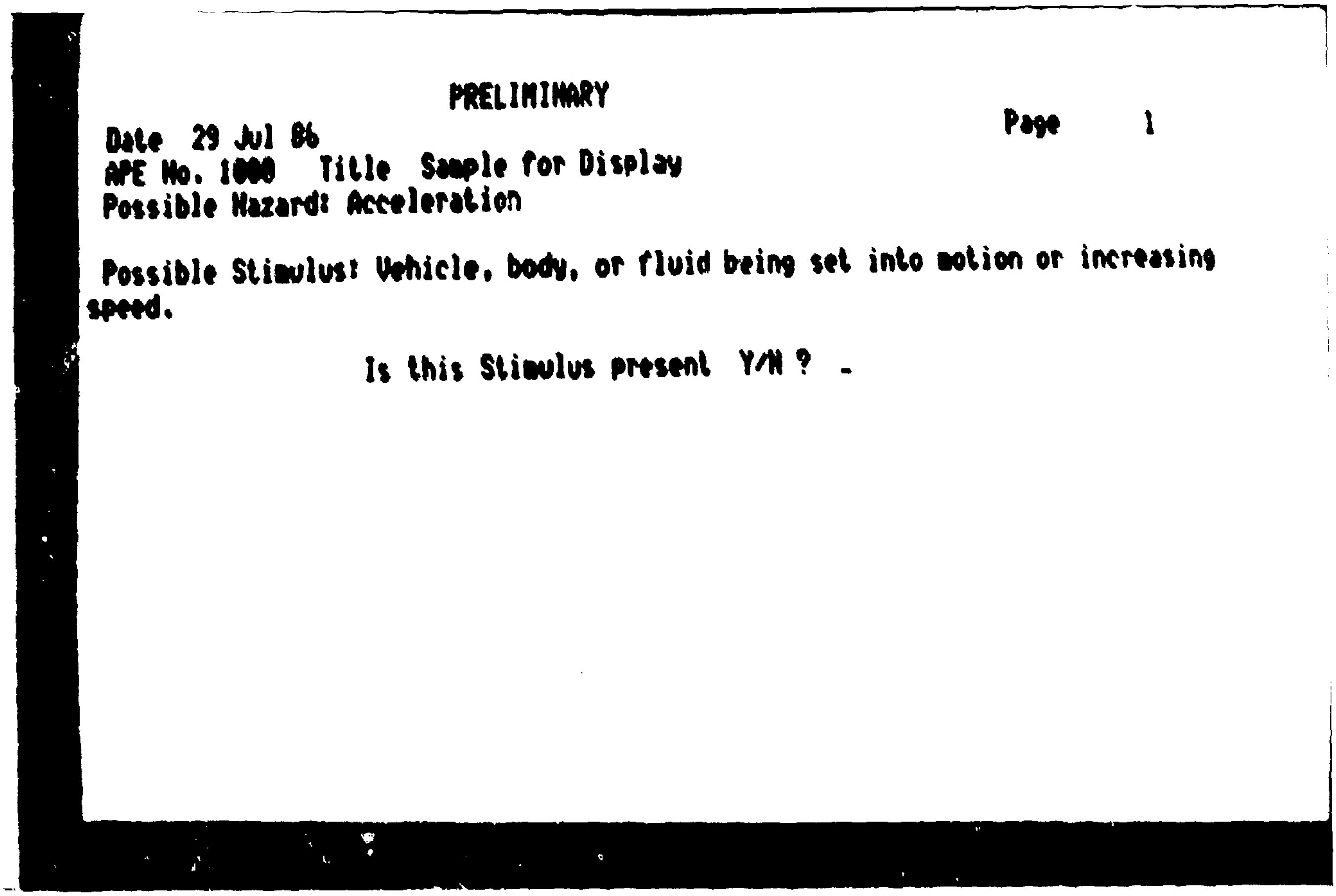
PSA SCREEN #1

This is the first screen of the PSA evaluation sequence.

If the safety evaluation was a System, Sub-system, Component or Operating and Support, HAZEL would have requested information above the item being evaluated.

If this hazard were not present, a "N" or "n" would be entered, and the next hazard would appear. This would continue until all hazards currently on the list were evaluated. HAZEL would then ask if a new hazard was to be entered, and if so, whether to add it to the permanent list for future use.

NOTE: At any time, pressing the "ESCAPE" key will terminate the evaluation process.



PRELIMINARY

Date 29 Jul 86 Page 1
APE No. 1000 Title Sample for Display
Possible Hazard: Acceleration

Possible Stimulus: Vehicle, body, or fluid being set into motion or increasing speed.

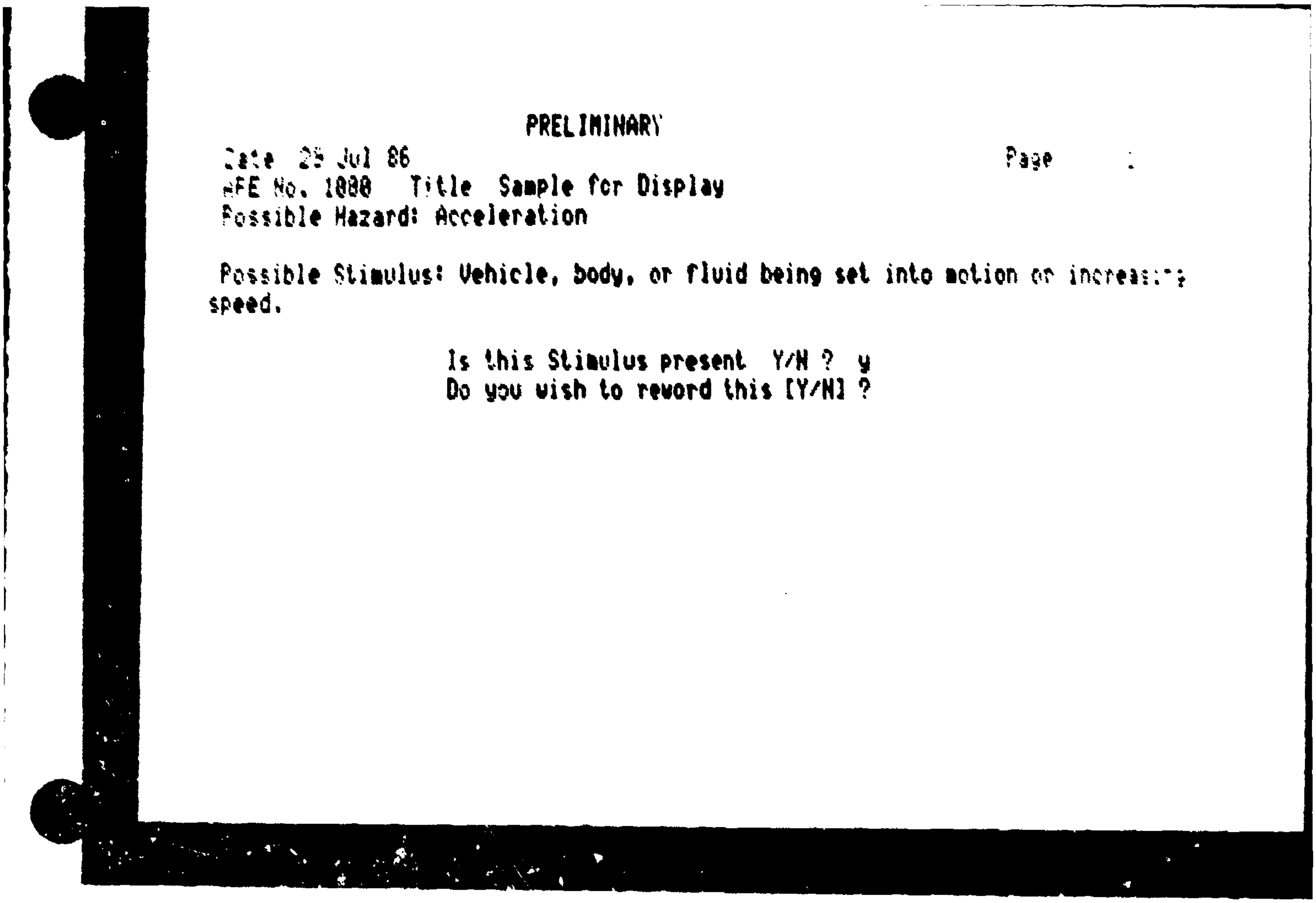
Is this Stimulus present Y/N ? _

PSA SCREEN #2A

The next step is to determine the stimulus through which the hazard would manifest itself.

If this stimulus were not present, a "N" or "n" would be entered, and the next stimulus would appear. This would continue until all stimulus currently on the list were evaluated. HAZEL would then ask if a new stimulus was to be entered, and if so, whether to add it to the permanent list for future use.

If this stimulus were present, HAZEL would continue with this screen.



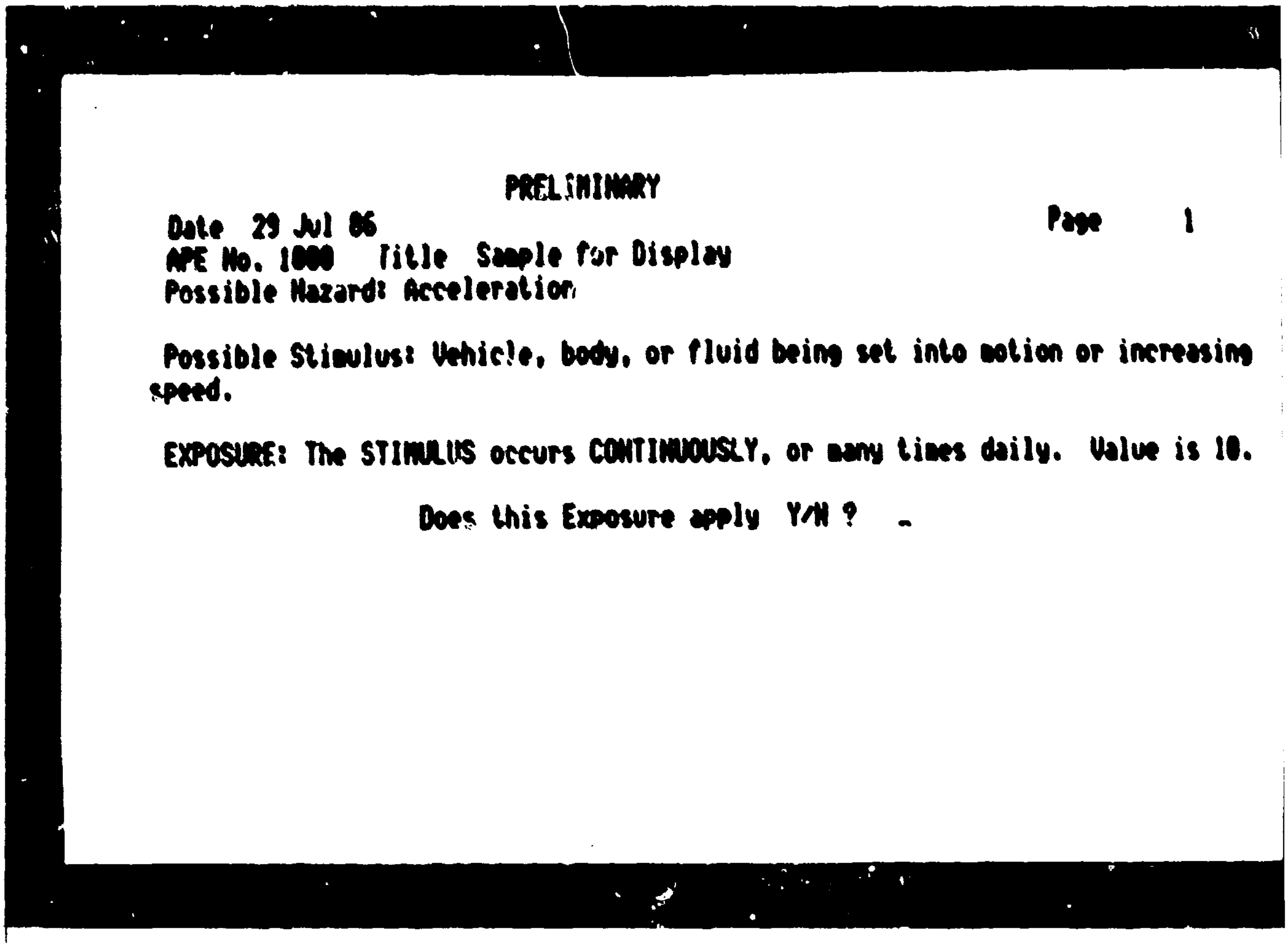
```
                         PRELIMINARY
 Date  25 Jul 86                                              Page      1
 AFE No. 1000   Title  Sample for Display
 Possible Hazard: Acceleration

 Possible Stimulus: Vehicle, body, or fluid being set into motion or increasing
speed.

                    Is this Stimulus present  Y/N ?  y
                    Do you wish to reword this [Y/N] ?
```

PSA SCREEN #2B

HAZEL would ask if this stimulus should be reworded.

If rewording is wished, HAZEL will ask for the rewording and then, ask i the rewording is correct. If not, HAZEL will continue until the correc rewording is entered. She will then continue with this screen.

If not, HAZEL will then continue with this screen.



PRELIMINARY

Date 29 Jul 86 Page 1

APE No. 1000 Title Sample for Display

Possible Hazard: Acceleration

Possible Stimulus: Vehicle, body, or fluid being set into motion or increasing speed.

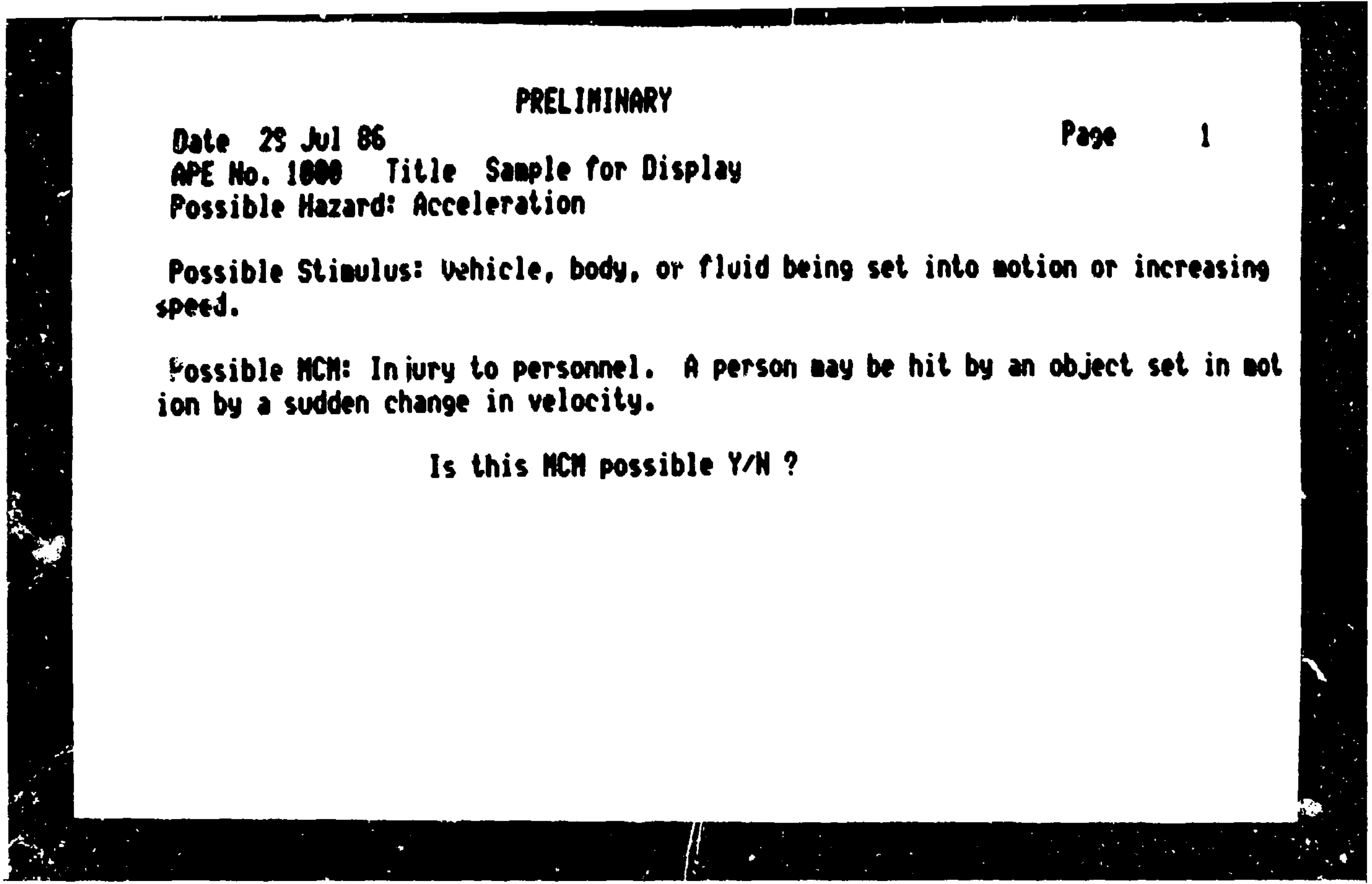
EXPOSURE: The STIMULUS occurs CONTINUOUSLY, or many times daily. Value is 10.

Does this Exposure apply Y/N ? _

PSA SCREEN #2C

This portion of the screen allows selection of the exposure. All exposure definitions will be presented and continued to be presented one at a time, until a selection is made.

Once selected, HAZEL will continue with this screen.



PRELIMINARY

Date 28 Jul 86 Page 1

APE No. 1000 Title Sample for Display

Possible Hazard: Acceleration

Possible Stimulus: Vehicle, body, or fluid being set into motion or increasing speed.

Possible MCM: Injury to personnel. A person may be hit by an object set in motion by a sudden change in velocity.

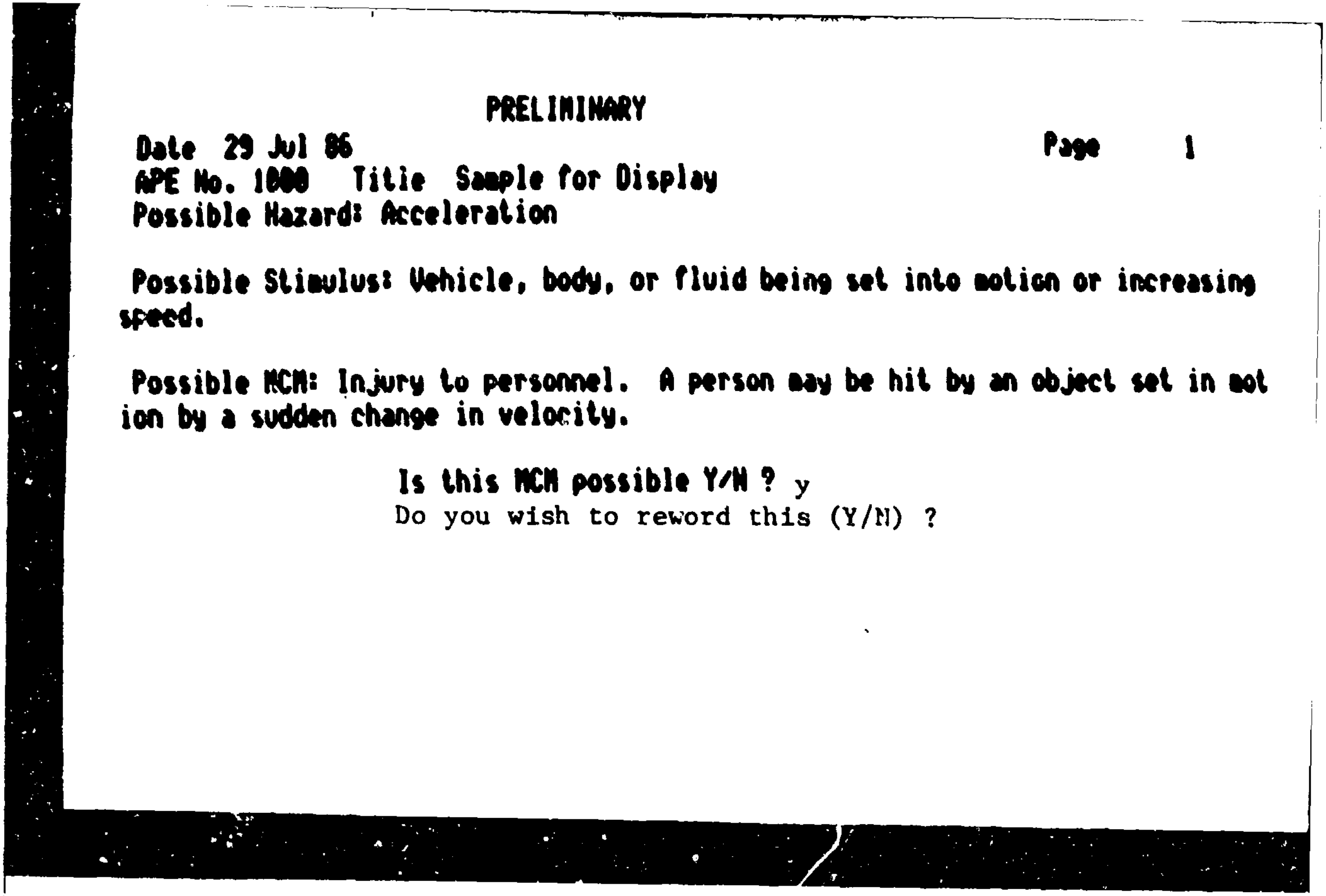
Is this MCM possible Y/N ?

PSA SCREEN #2D

The next step is to determine the MCM.

If this MCM were not possible, a "N" or "n" would be entered, and the next MCM would appear. This would continue until all MCMs currently on the list were evaluated. HAZEL would then ask if a new MCM was to be entered, and if so whether to add it to the permanent list for future use.

If this MCM were possible, HAZEL would continue with this screen.



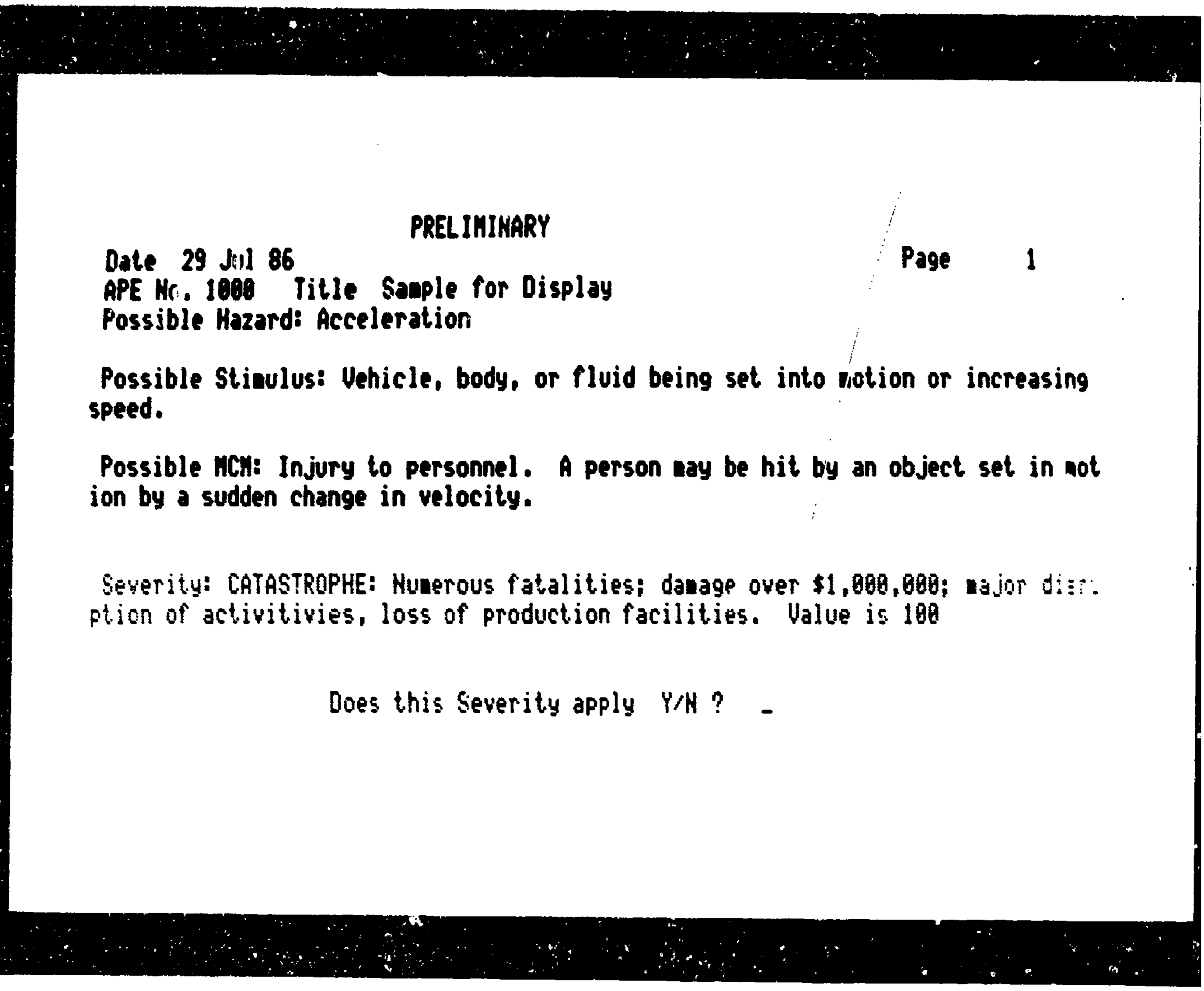
```
                              PRELIMINARY
  Date 29 Jul 86                                                  Page      1
  APE No. 1000   Title  Sample for Display
  Possible Hazard: Acceleration

  Possible Stimulus: Vehicle, body, or fluid being set into motion or increasing
 speed.

  Possible MCM: Injury to personnel.  A person may be hit by an object set in mot
 ion by a sudden change in velocity.

                         Is this MCM possible Y/N ? y
                         Do you wish to reword this (Y/N) ?
```

PSA SCREEN #2E

HAZEL would ask if this MCM should be reworded.

If rewording is wished, HAZEL will ask for the rewording and then ask if the rewording is correct. If not, HAZEL will continue until the correct rewording is entered. She will then continue with this screen.

If no rewording is required, HAZEL will then continue with this screen.



PRELIMINARY

Date 29 Jul 86 Page 1

APE No. 1000 Title Sample for Display

Possible Hazard: Acceleration

Possible Stimulus: Vehicle, body, or fluid being set into motion or increasing speed.

Possible MCM: Injury to personnel. A person may be hit by an object set in motion by a sudden change in velocity.

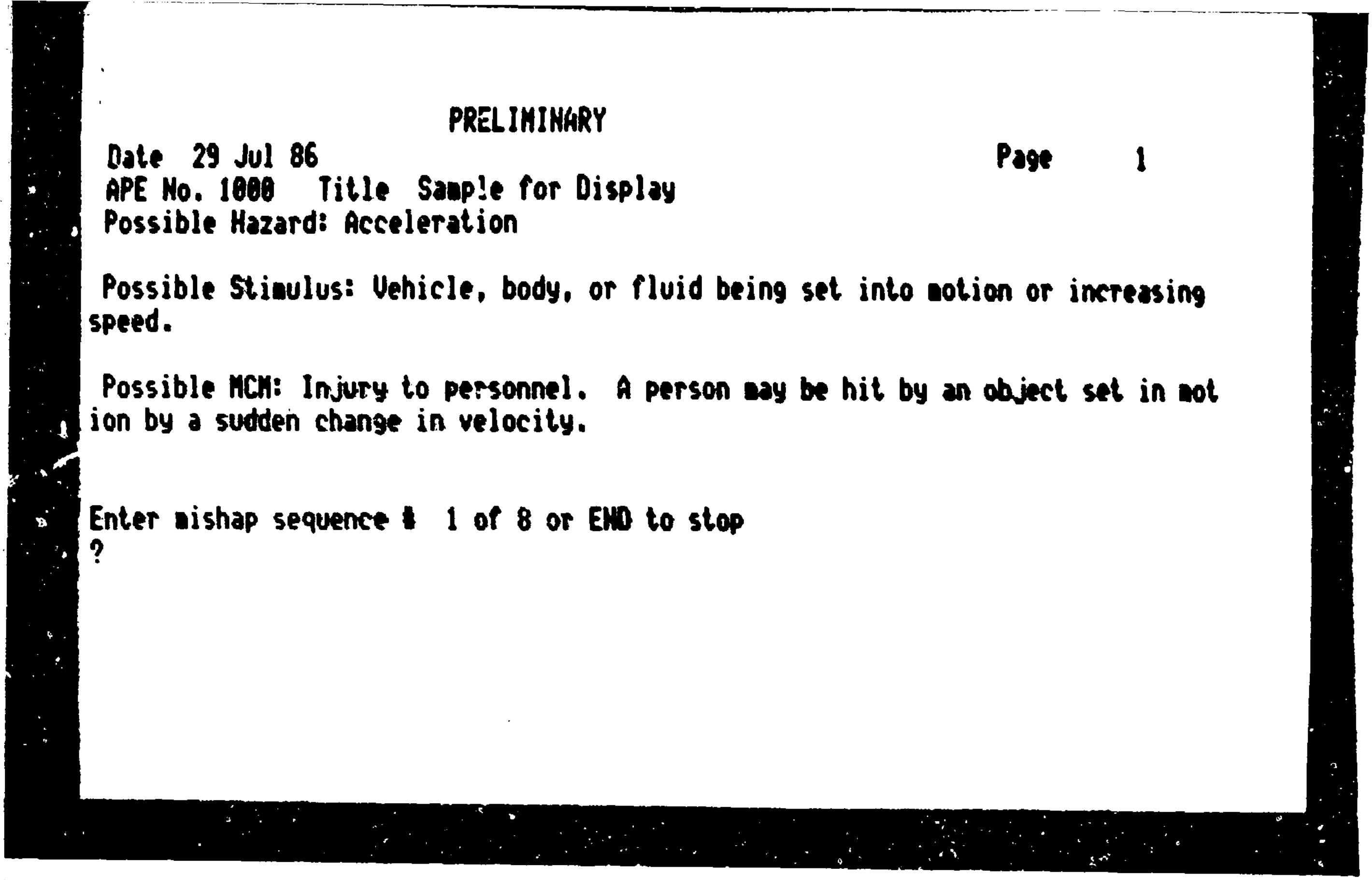
Severity: CATASTROPHE: Numerous fatalities; damage over $1,000,000; major disruption of activitivies, loss of production facilities. Value is 100

Does this Severity apply Y/N ? _

PSA SCREEN #2F

This portion of the screen allows selection of the severity. All severity definitions will be presented and continue to be presented one at a time, until a selection is made.

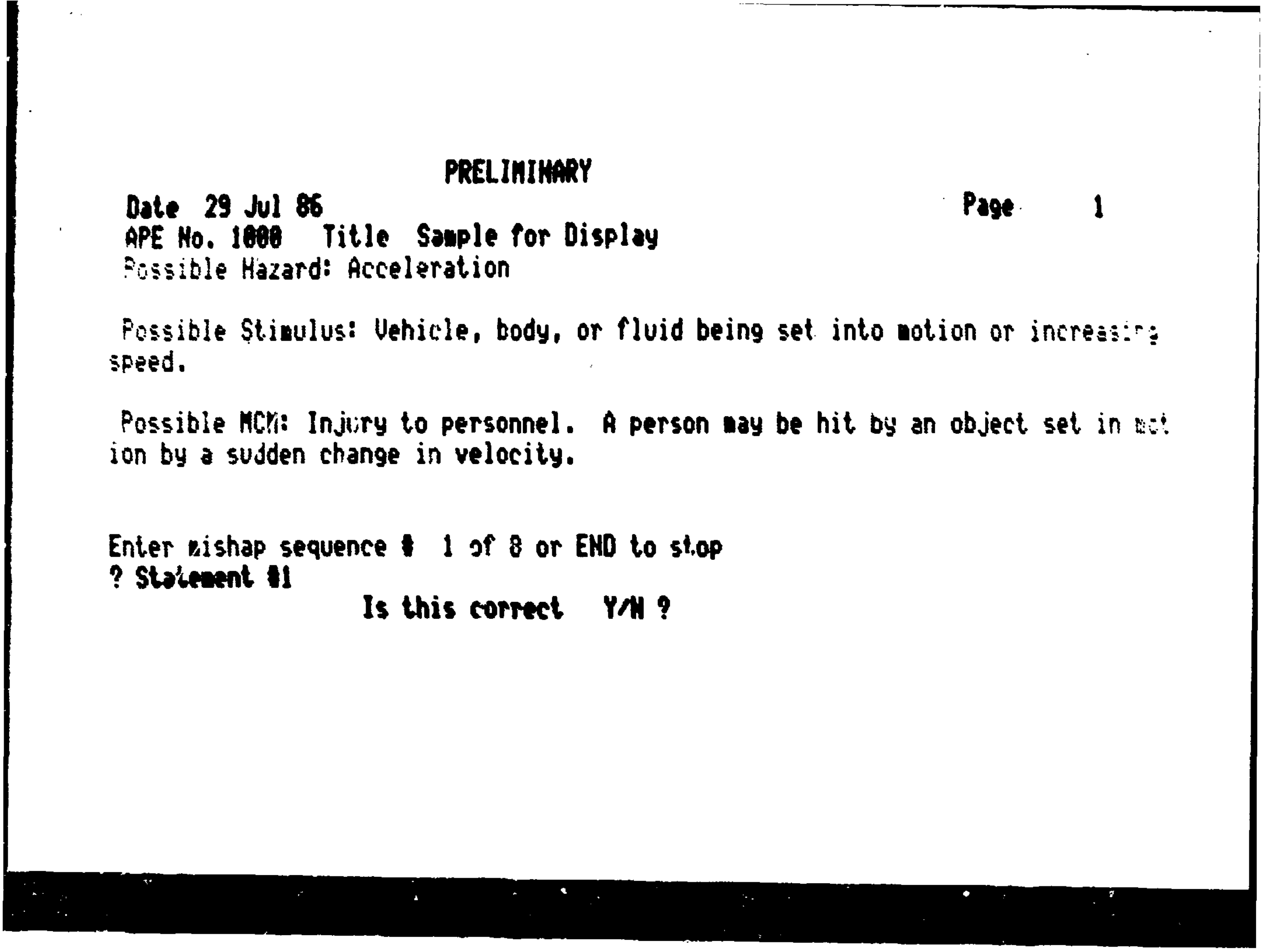
Once selected, HAZEL will continue with this screen.



```
                         PRELIMINARY
Date  29 Jul 86                                          Page      1
APE No. 1000   Title  Sample for Display
Possible Hazard: Acceleration

 Possible Stimulus: Vehicle, body, or fluid being set into motion or increasing
speed.

 Possible MCM: Injury to personnel.  A person may be hit by an object set in mot
ion by a sudden change in velocity.


Enter mishap sequence #  1 of 8 or END to stop
?
```

PSA SCREEN #2G

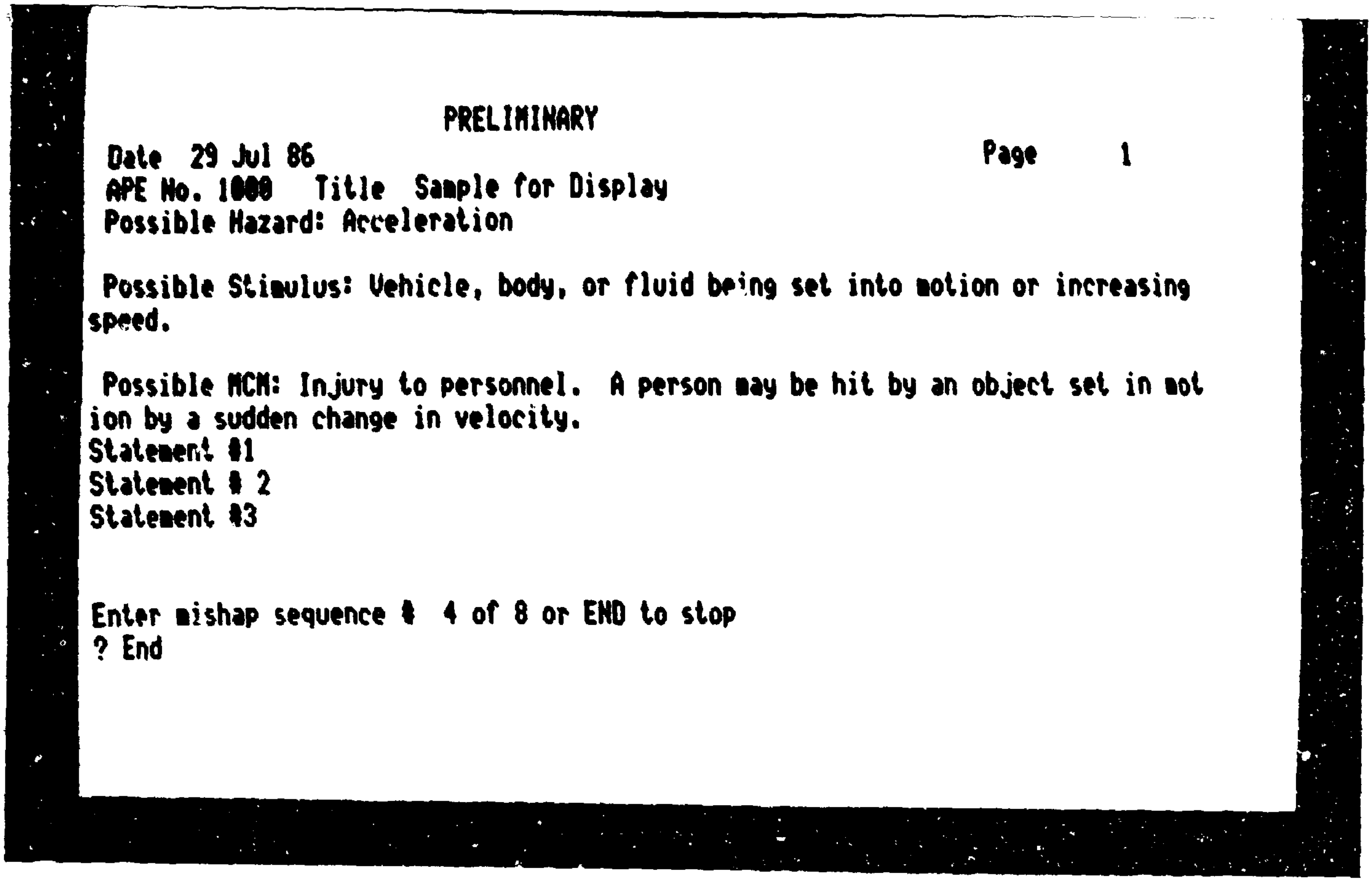
The next step is to enter the mishap sequence.



```
                          PRELIMINARY
 Date  29 Jul 86                                               Page      1
 APE No. 1000   Title  Sample for Display
 Possible Hazard: Acceleration

 Possible Stimulus: Vehicle, body, or fluid being set into motion or increasing
speed.

 Possible MCM: Injury to personnel.  A person may be hit by an object set in mot
ion by a sudden change in velocity.


Enter mishap sequence #  1 of 8 or END to stop
? Statement #1
                 Is this correct   Y/N ?
```

PSA SCREEN #2H

HAZEL will ask if this statement is correct.



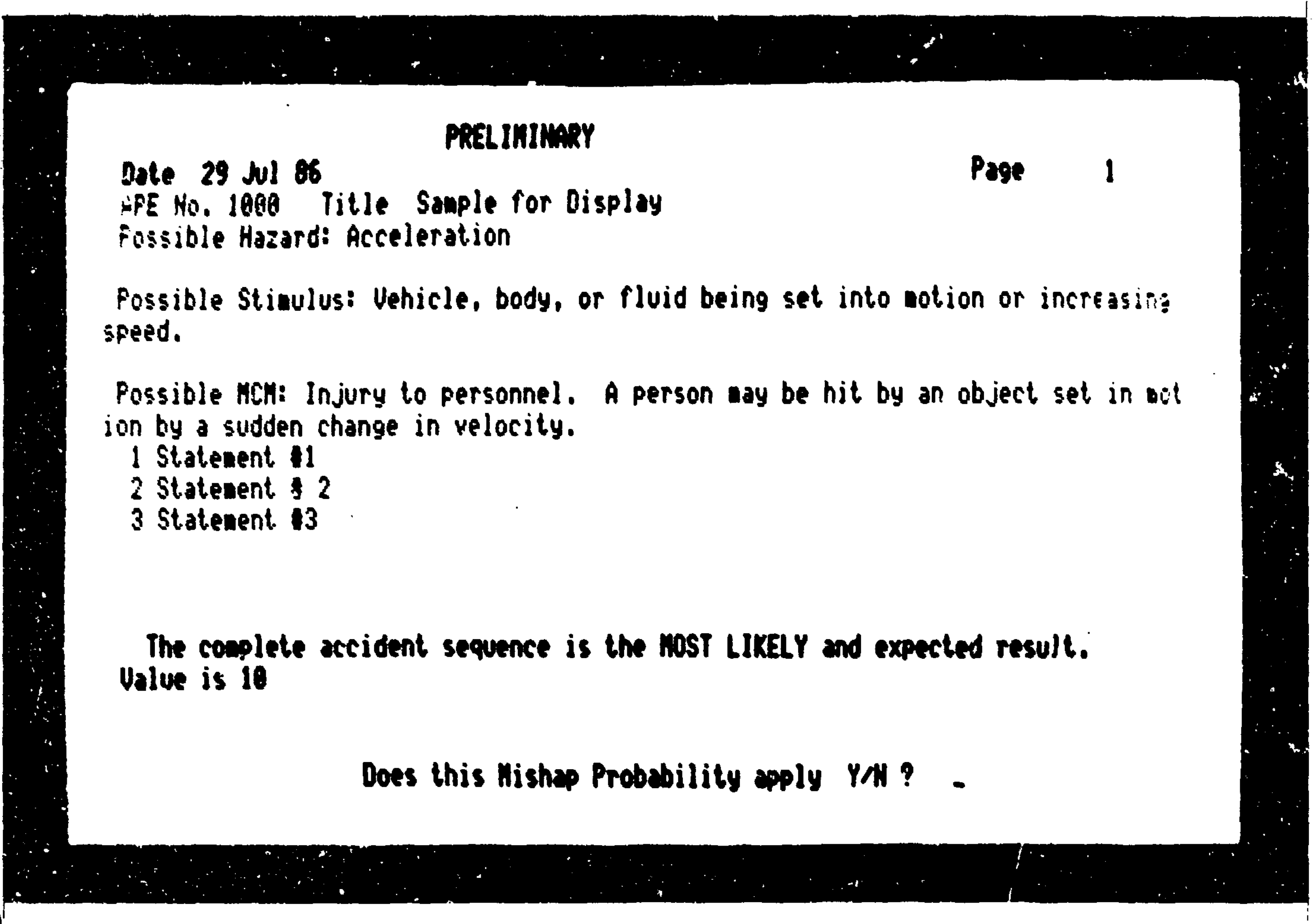
```
                              PRELIMINARY
 Date  29 Jul 86                                                Page      1
 APE No. 1000   Title  Sample for Display
 Possible Hazard: Acceleration

 Possible Stimulus: Vehicle, body, or fluid being set into motion or increasing
speed.

 Possible MCM: Injury to personnel.  A person may be hit by an object set in mot
ion by a sudden change in velocity.
Statement #1
Statement # 2
Statement #3


Enter mishap sequence #  4 of 8 or END to stop
? End
```

PSA SCREEN #21

HAZEL will permit the input of up to 8 lines of 80 characters for each mishap sequence.

To end entering them, "End", "end" or "END" is entered.

HAZEL then continues with this screen.



PRELIMINARY

Date 29 Jul 86 Page 1

MPE No. 1000 Title Sample for Display

Possible Hazard: Acceleration

Possible Stimulus: Vehicle, body, or fluid being set into motion or increasing speed.

Possible MCM: Injury to personnel. A person may be hit by an object set in motion by a sudden change in velocity.

1 Statement #1

2 Statement # 2

3 Statement #3

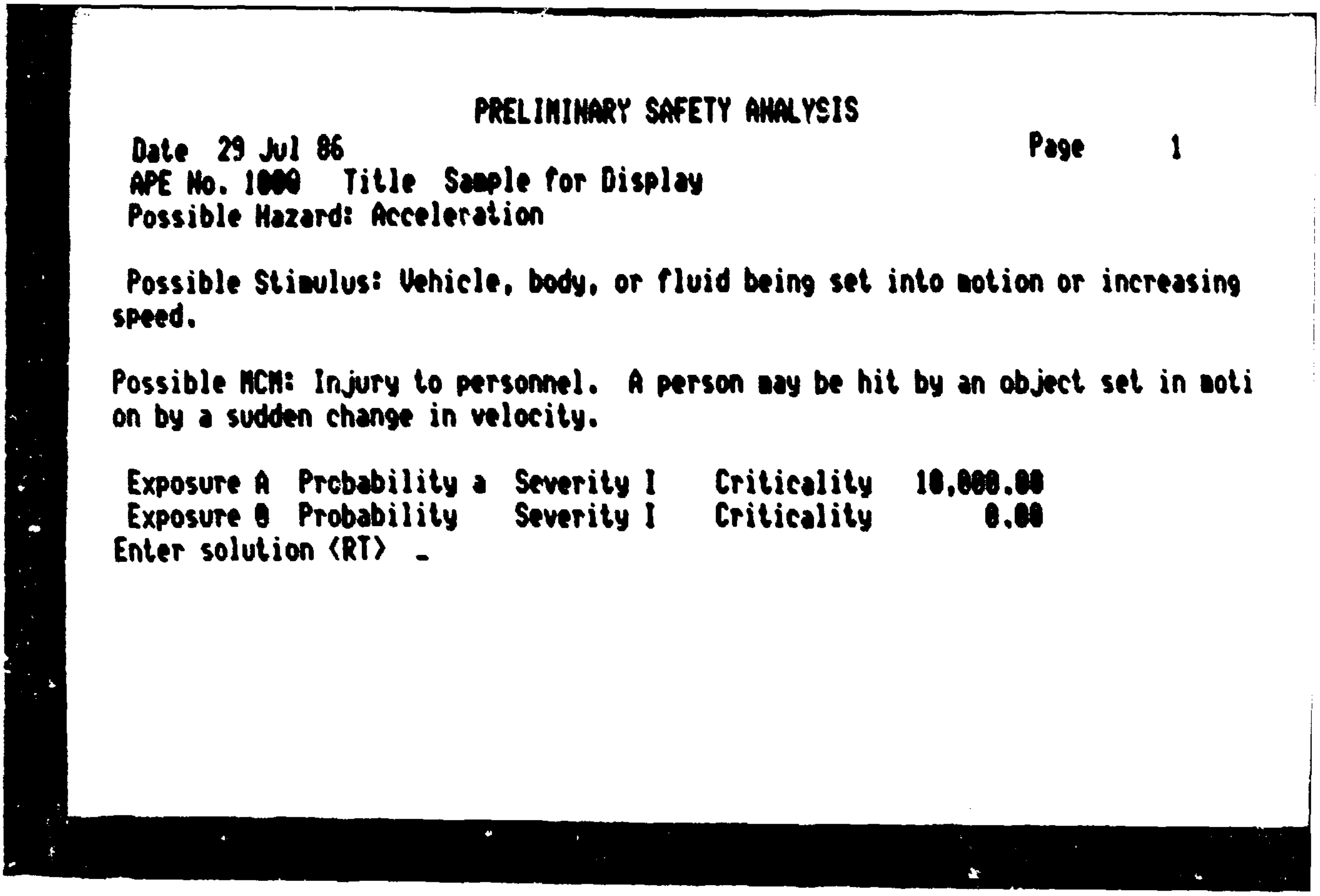
The complete accident sequence is the MOST LIKELY and expected result.

Value is 10

Does this Mishap Probability apply Y/N ?

PSA SCREEN #2J

This portion of the screen allows selection of the mishap probability. All mishap probability definitions will be presented and continue to be presented one at a time, until a selection is made.

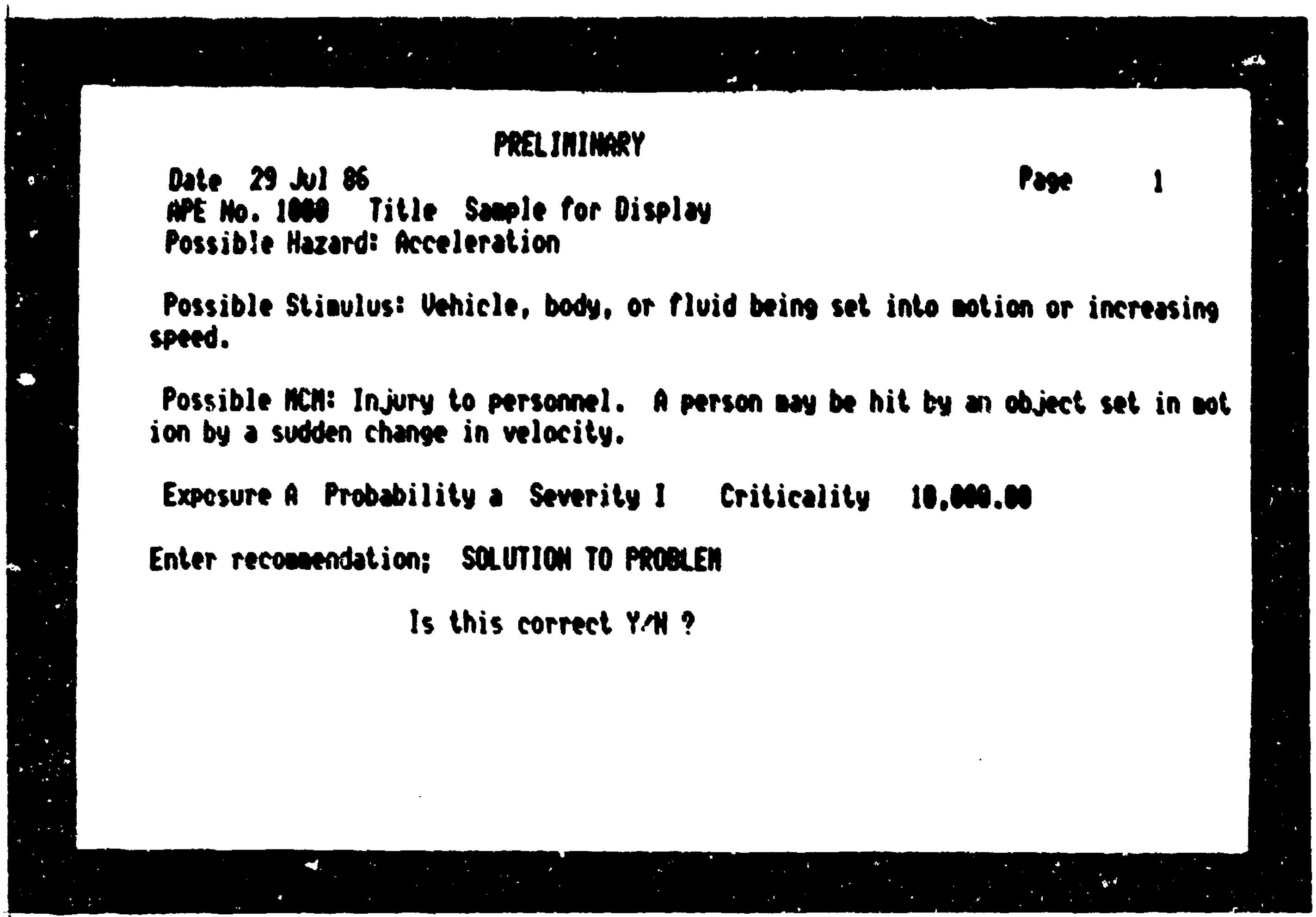


```
                     PRELIMINARY SAFETY ANALYSIS
  Date  29 Jul 86                                             Page      1
  APE No. 1000   Title  Sample for Display
  Possible Hazard: Acceleration

  Possible Stimulus: Vehicle, body, or fluid being set into motion or increasing
 speed.

 Possible MCM: Injury to personnel.  A person may be hit by an object set in moti
 on by a sudden change in velocity.

  Exposure A  Probability a  Severity I    Criticality   10,000.00
  Exposure 0  Probability    Severity I    Criticality        0.00
 Enter solution <RT>  _
```

PSA SCREEN #2K

If the criticality is greater than 10, then HAZEL will request a recommended solution be entered.

If the criticality is 10 or less, HAZEL will indicate no solution is required.

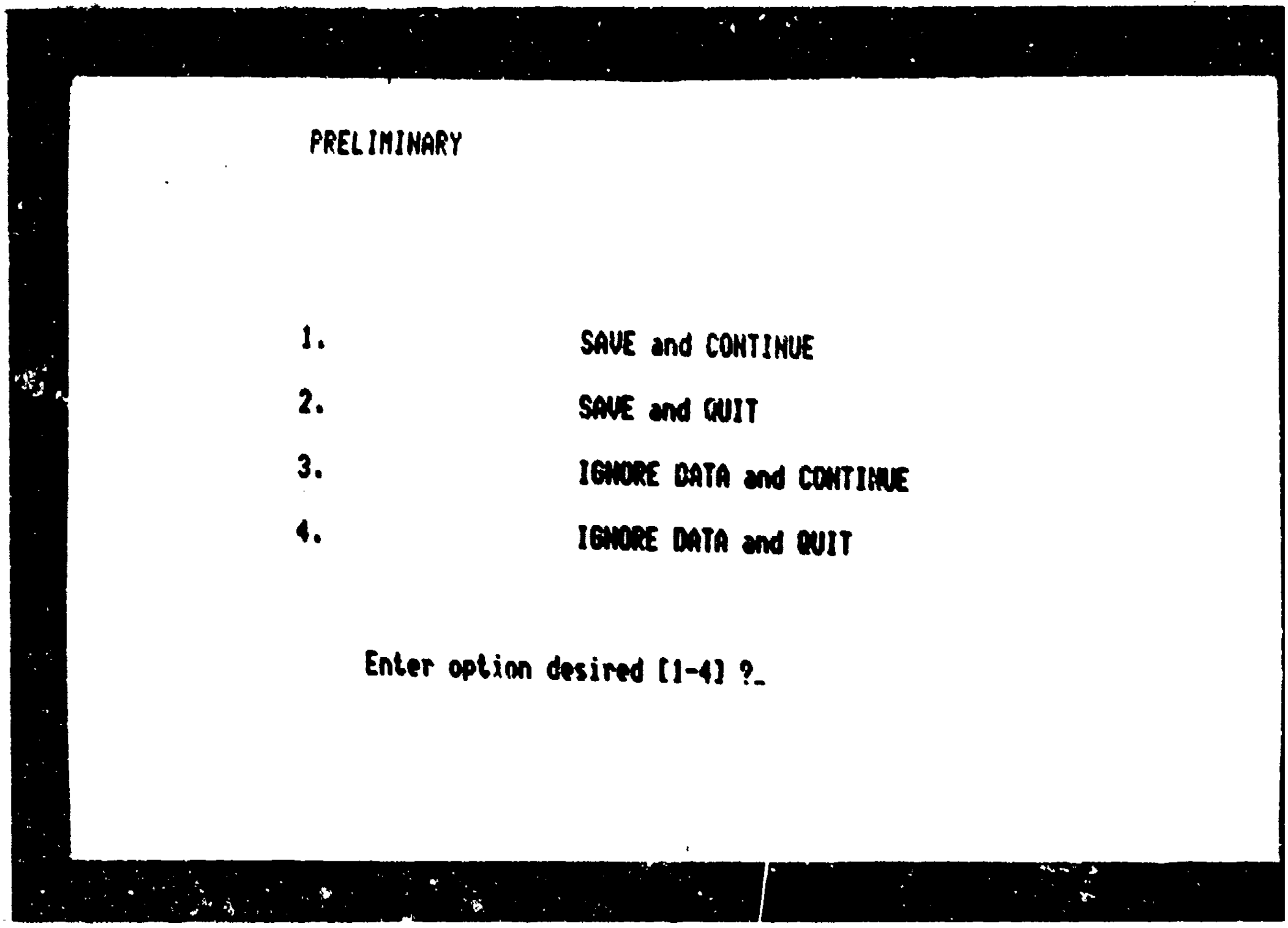


```
                         PRELIMINARY
  Date  29 Jul 86                                          Page     1
  APE No. 1000   Title  Sample for Display
  Possible Hazard: Acceleration

 Possible Stimulus: Vehicle, body, or fluid being set into motion or increasing
speed.

 Possible MCM: Injury to personnel.  A person may be hit by an object set in mot
ion by a sudden change in velocity.

 Exposure A  Probability a  Severity I    Criticality   10,000.00

Enter recommendation;  SOLUTION TO PROBLEM

                    Is this correct Y/N ?
```

PSA SCREEN #7L

HAZEL will ask if the solution is correct, if not, she will allow it to be reentered.

Otherwise yes is entered and a new screen appears.


PRELIMINARY

1. SAVE and CONTINUE
2. SAVE and QUIT
3. IGNORE DATA and CONTINUE
4. IGNORE DATA and QUIT

Enter option desired [1-4] ?_

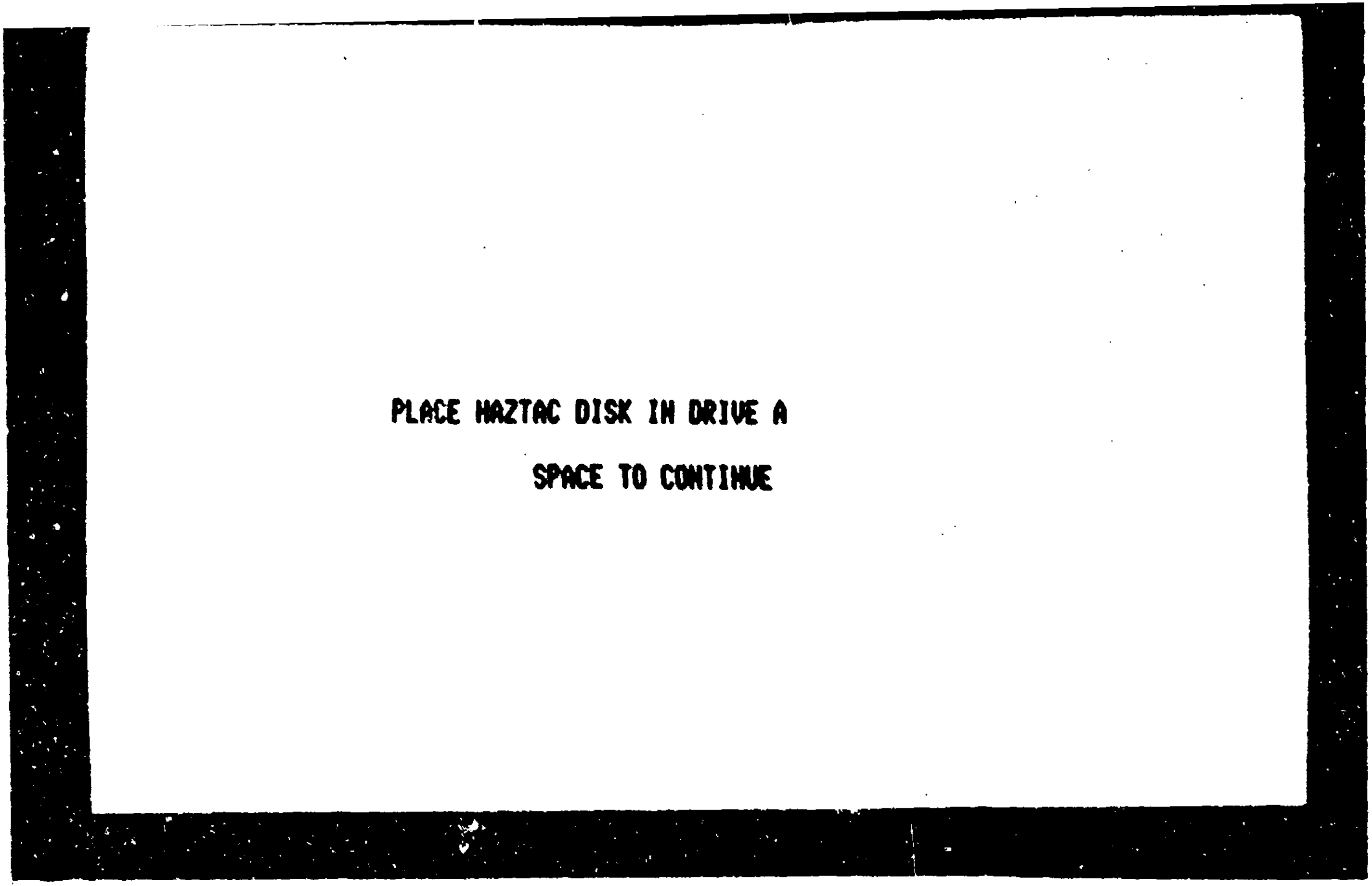
PSA SCREEN #3

This screen allows selection of how to handle the data entered.

If option 1 or 2 is selected, the safety evaluation page will be printed out.

If option 1 or 3 is selected, HAZEL will proceed to PSA screen #1. The same hazard will be present which had just been completed, in case it can be manifested by more than one stimulus.

If option 2 or 4 is selected, HAZEL will proceed to PSA screen #4.



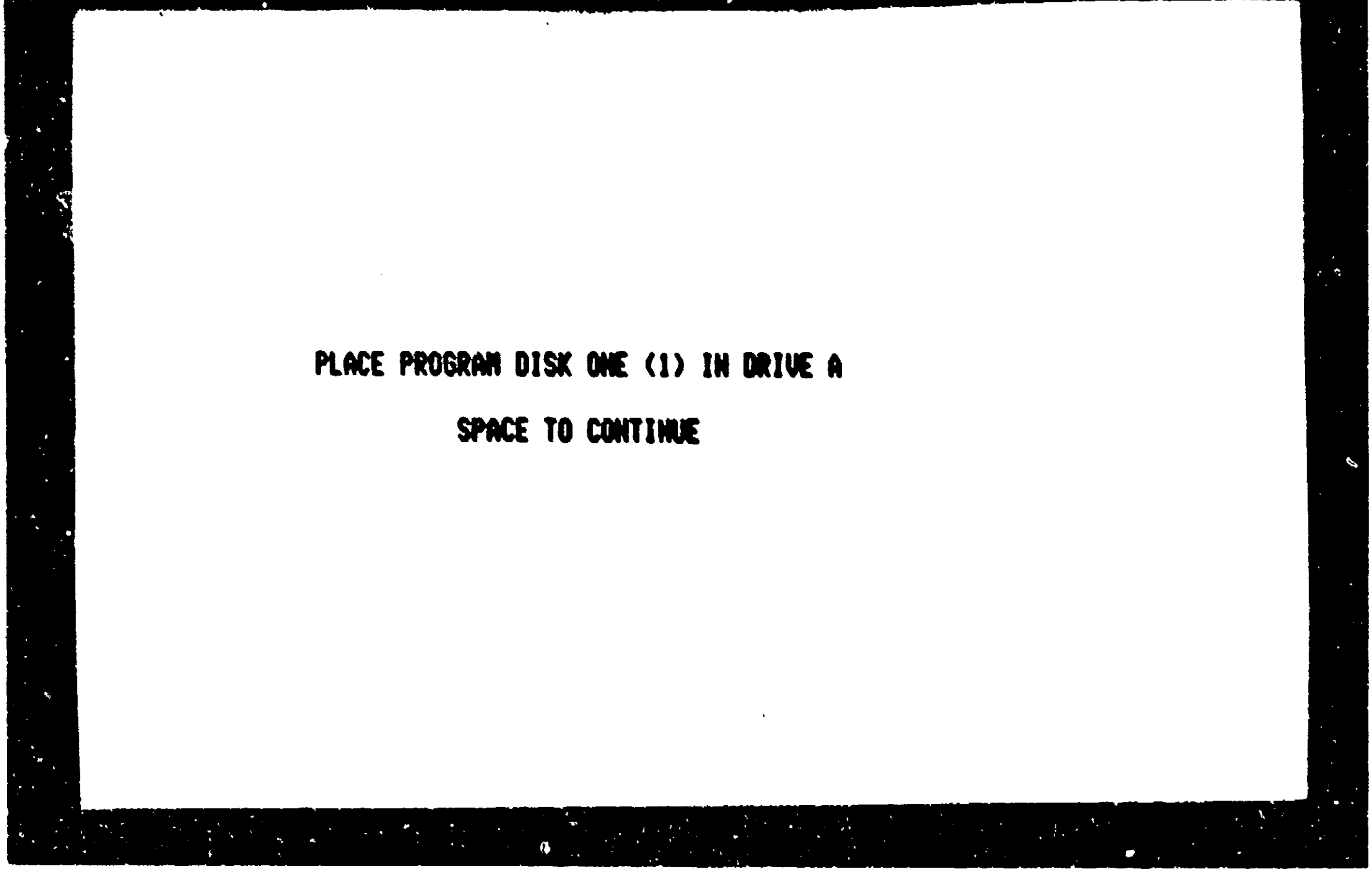
PLACE HAZTAC DISK IN DRIVE A

SPACE TO CONTINUE

PSA SCREEN #4

HAZEL then requests that the HAZTAC disk be placed in Drive A and checks to insure it was.

She then proceeds to update the HAZTAC file, with the new safety deficiencies determined.

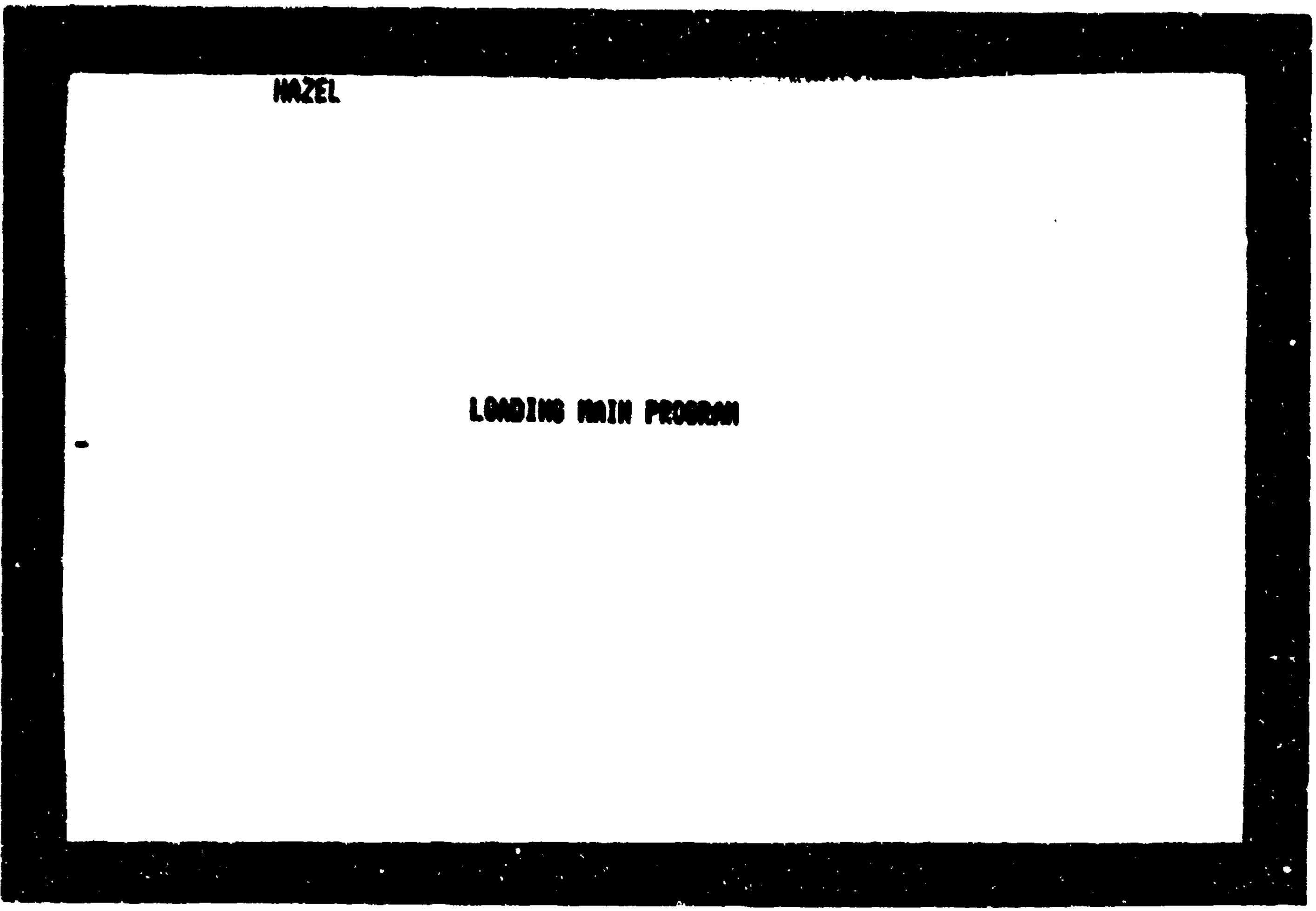


PLACE PROGRAM DISK ONE (1) IN DRIVE A

SPACE TO CONTINUE

PSA SCREEN #5

After updating the file, she asks for the first program disk to be place in Drive A.

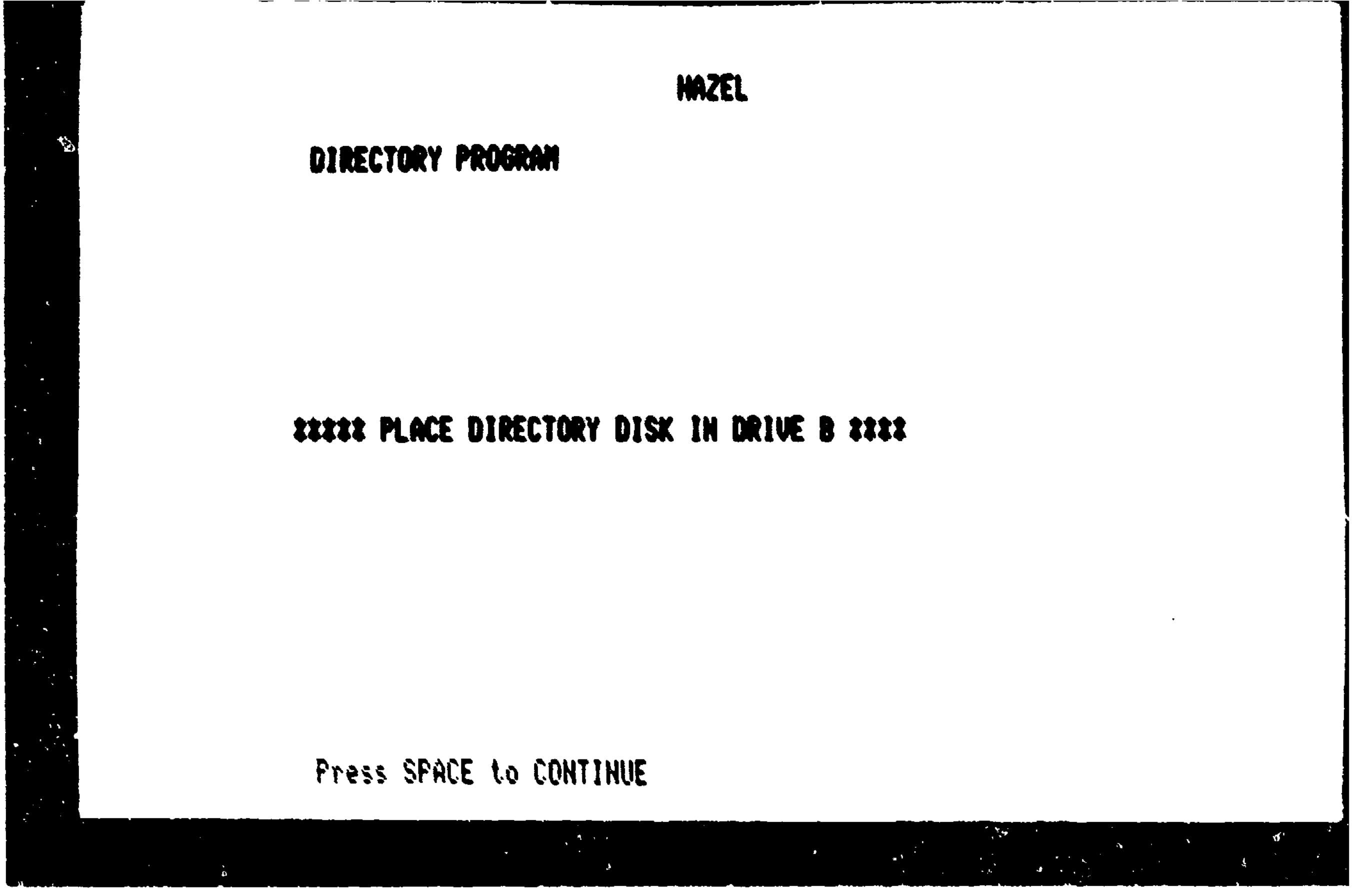


HAZEL

LOADING MAIN PROGRAM

PSA SCREEN #6

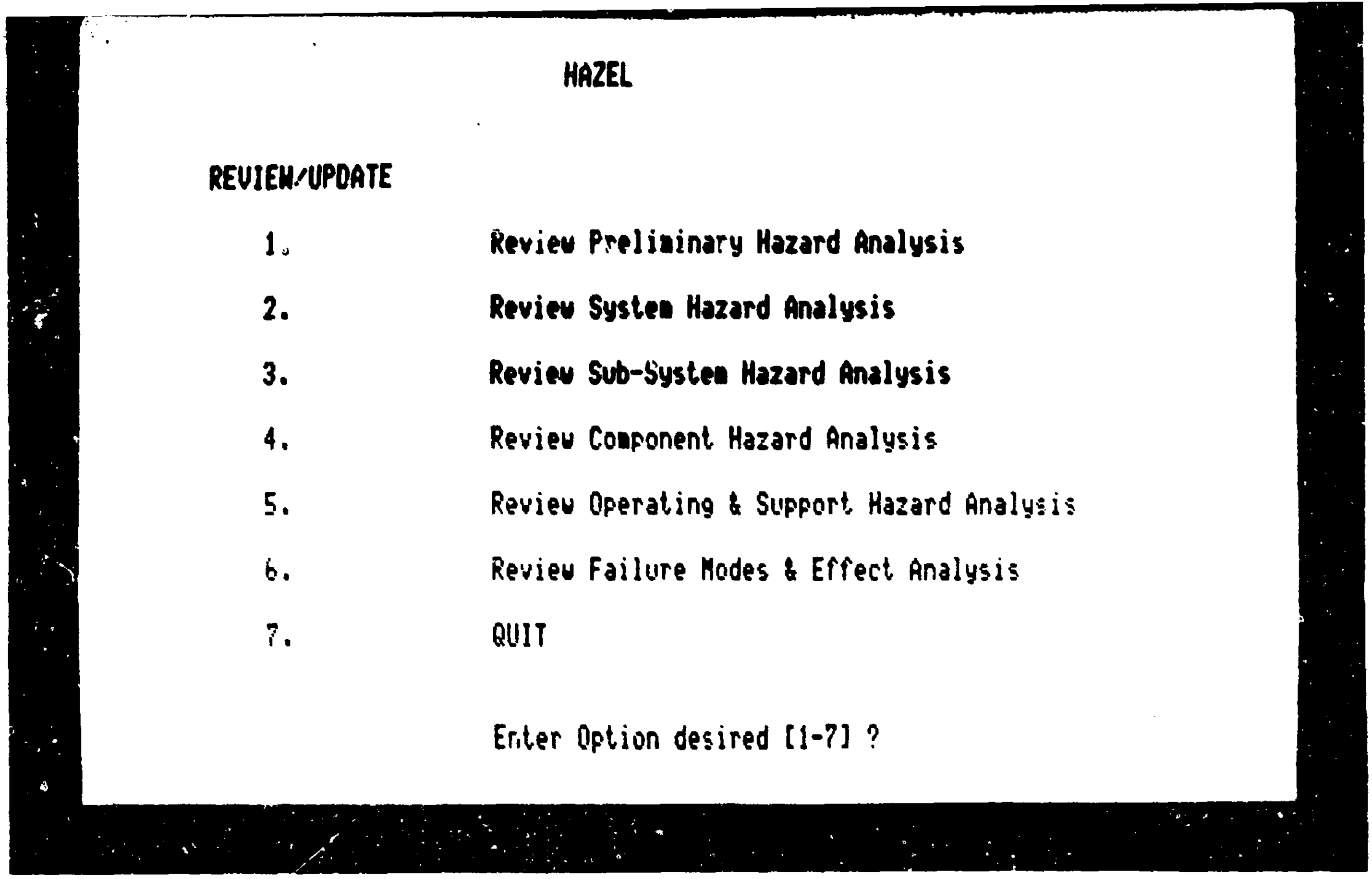
She then loads the main program.



```
                        HAZEL

        DIRECTORY PROGRAM



      ***** PLACE DIRECTORY DISK IN DRIVE B ****



        Press SPACE to CONTINUE
```

PSA SCREEN #7

She then requests and checks for the presence of the Directory Disk in Drive B. Once in place, she updates the master file for the system being evaluated.



HAZEL

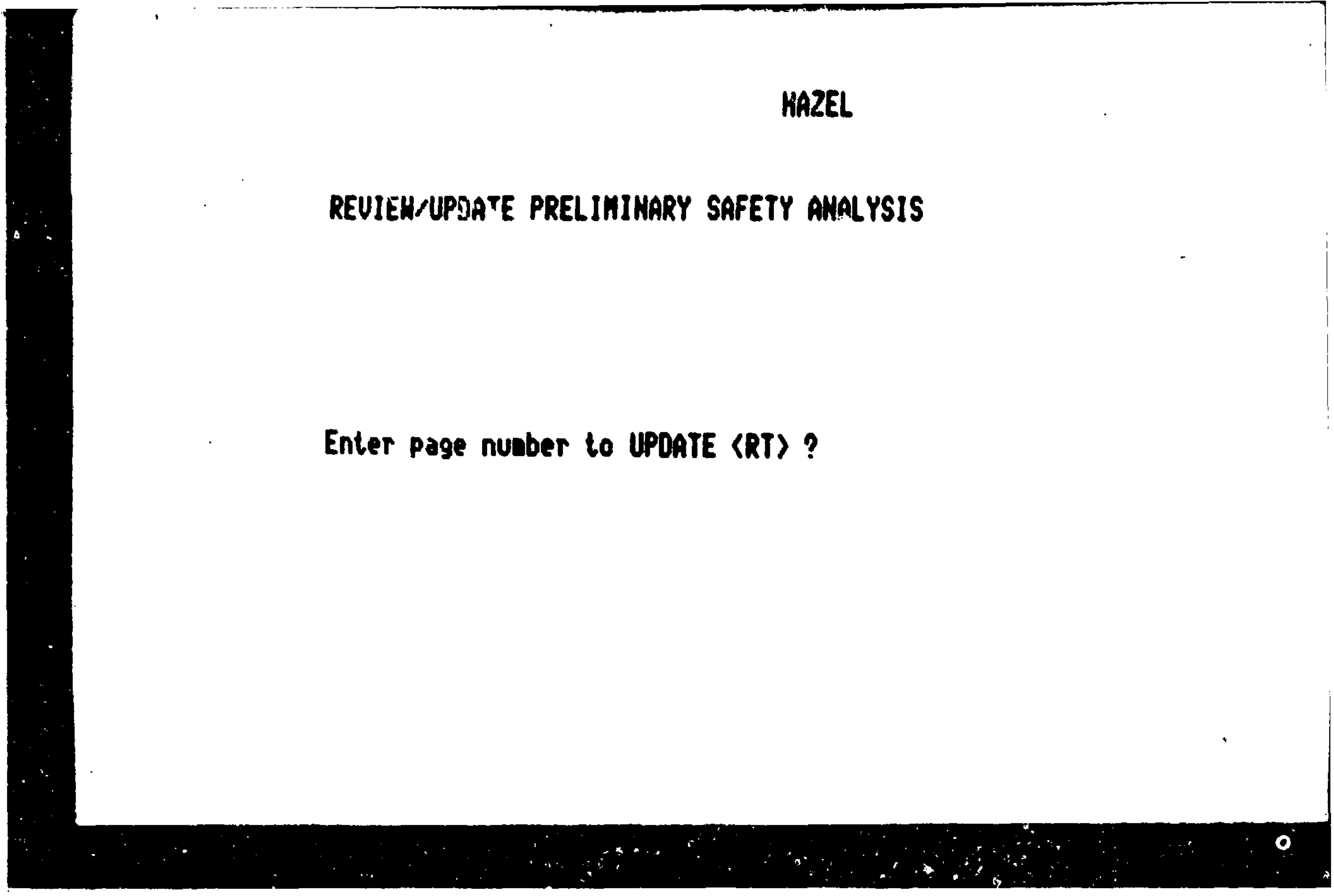
REVIEW/UPDATE

1. Review Preliminary Hazard Analysis
2. Review System Hazard Analysis
3. Review Sub-System Hazard Analysis
4. Review Component Hazard Analysis
5. Review Operating & Support Hazard Analysis
6. Review Failure Modes & Effect Analysis
7. QUIT

Enter Option desired [1-7] ?

PSA SCREEN #8

If the project were to be reviewed or updated, this menu would appear after selecting the Review/Update option of Master Menu #1.



HAZEL

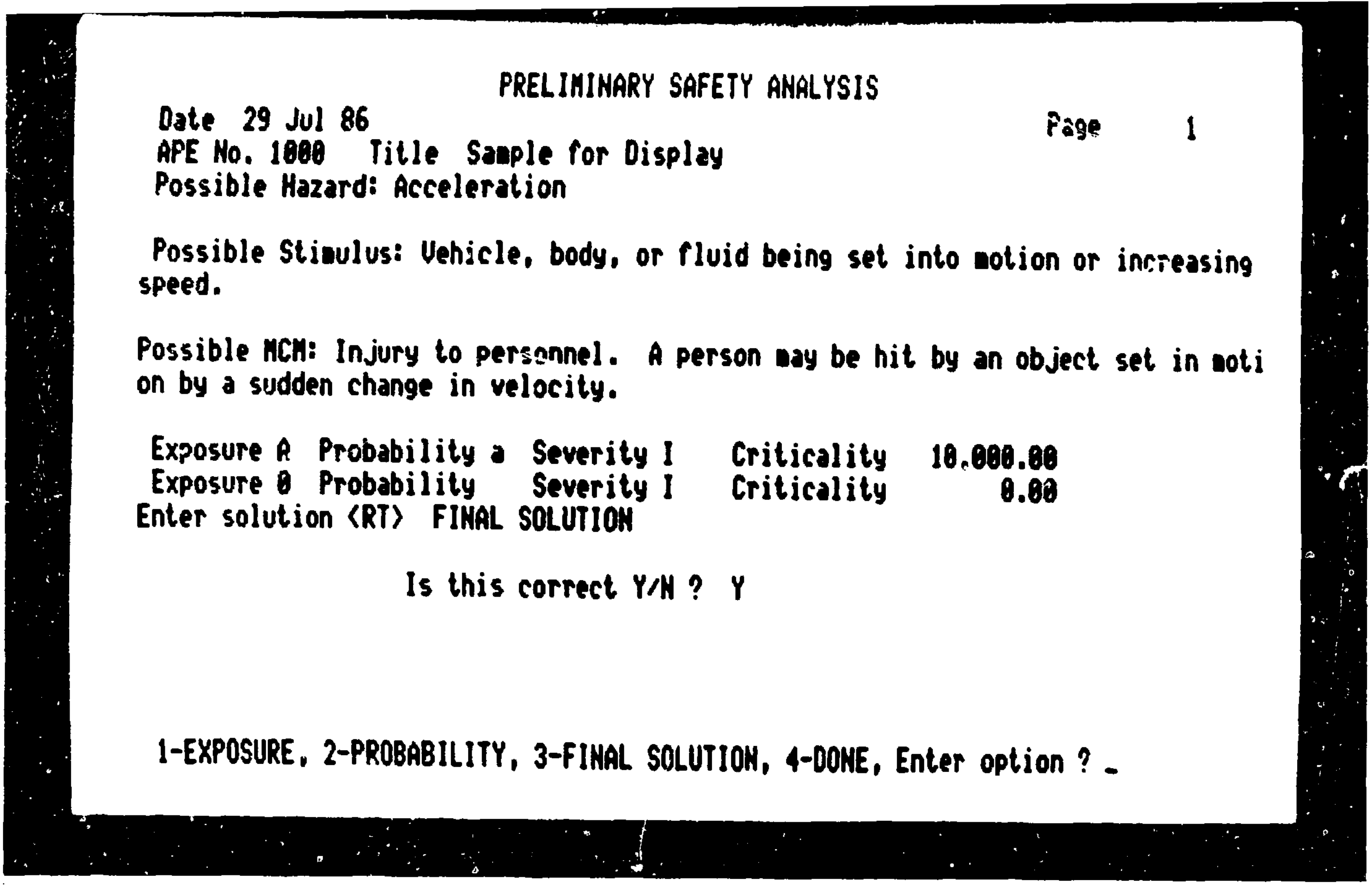
REVIEW/UPDATE PRELIMINARY SAFETY ANALYSIS

Enter page number to UPDATE <RT> ?

PSA SCREEN #9

After checking to see what system was being evaluated, and loading the correct evaluation disk in Drive B, HAZEL would request the page number of the safety analysis to be updated.

If the safety deficiency has already been closed, HAZEL proceeds directly to screen #11, otherwise, she proceeds to screen #10A.



```
                    PRELIMINARY SAFETY ANALYSIS
 Date  29 Jul 86                                          Page      1
 APE No. 1000   Title  Sample for Display
 Possible Hazard: Acceleration

 Possible Stimulus: Vehicle, body, or fluid being set into motion or increasing
speed.

Possible MCM: Injury to personnel.  A person may be hit by an object set in moti
on by a sudden change in velocity.

 Exposure A  Probability a  Severity I    Criticality   10,000.00
 Exposure 0  Probability    Severity I    Criticality        0.00
Enter solution <RT>  FINAL SOLUTION

                     Is this correct Y/N ?  Y



 1-EXPOSURE, 2-PROBABILITY, 3-FINAL SOLUTION, 4-DONE, Enter option ? _
```

PSA SCREEN #10A

This is the first of two screens required to update a safety analysis page.

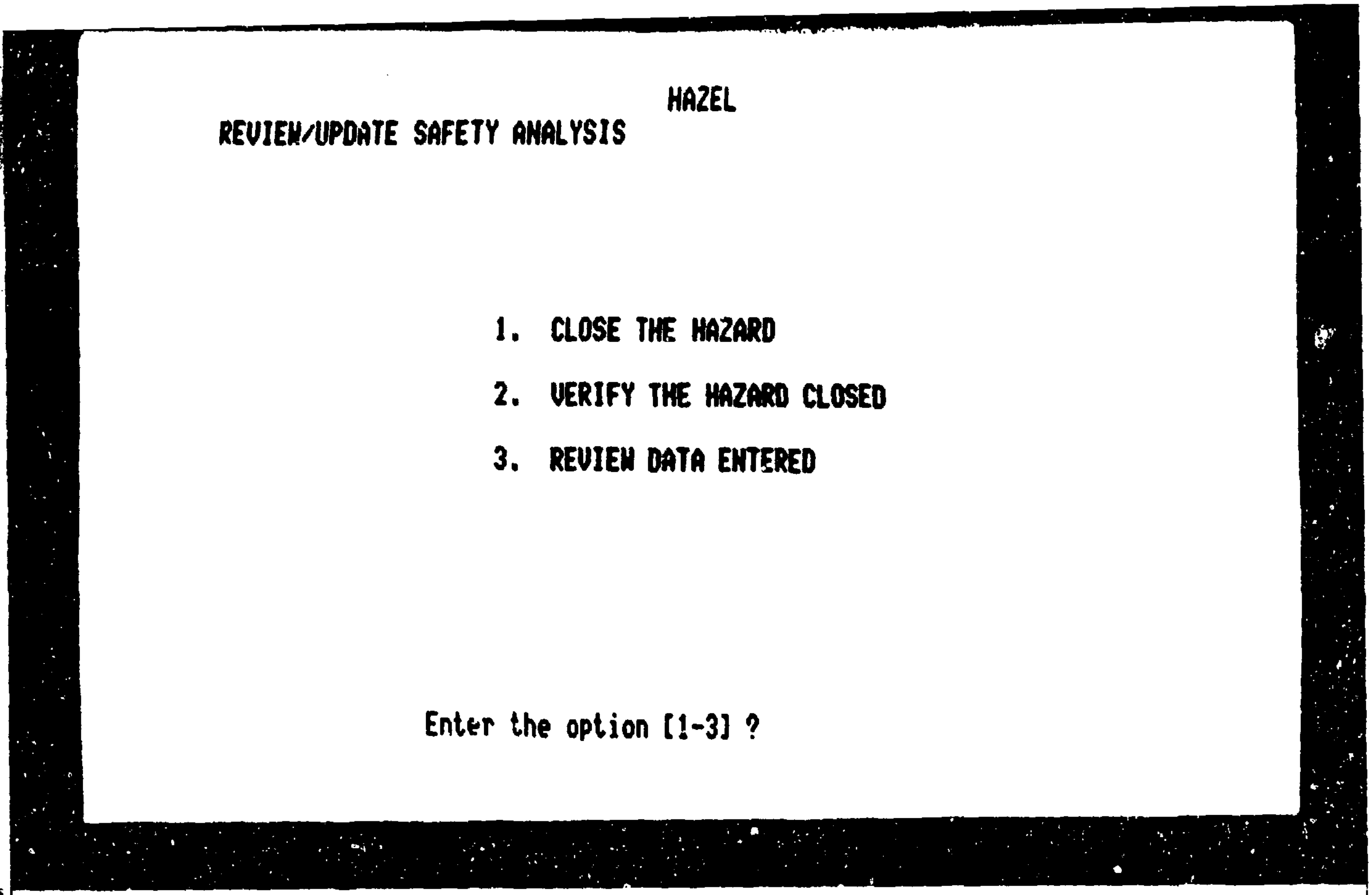
HAZEL first requests the final solution to be entered and then permits selection of options to update.

To select the final exposure of the hazard, a "1" is entered.

To select the final mishap probability, a "2" is selected.

If the final solution requires change, then "3" can be entered.

When satisfied with these entries, the next screen can be selected using "4".



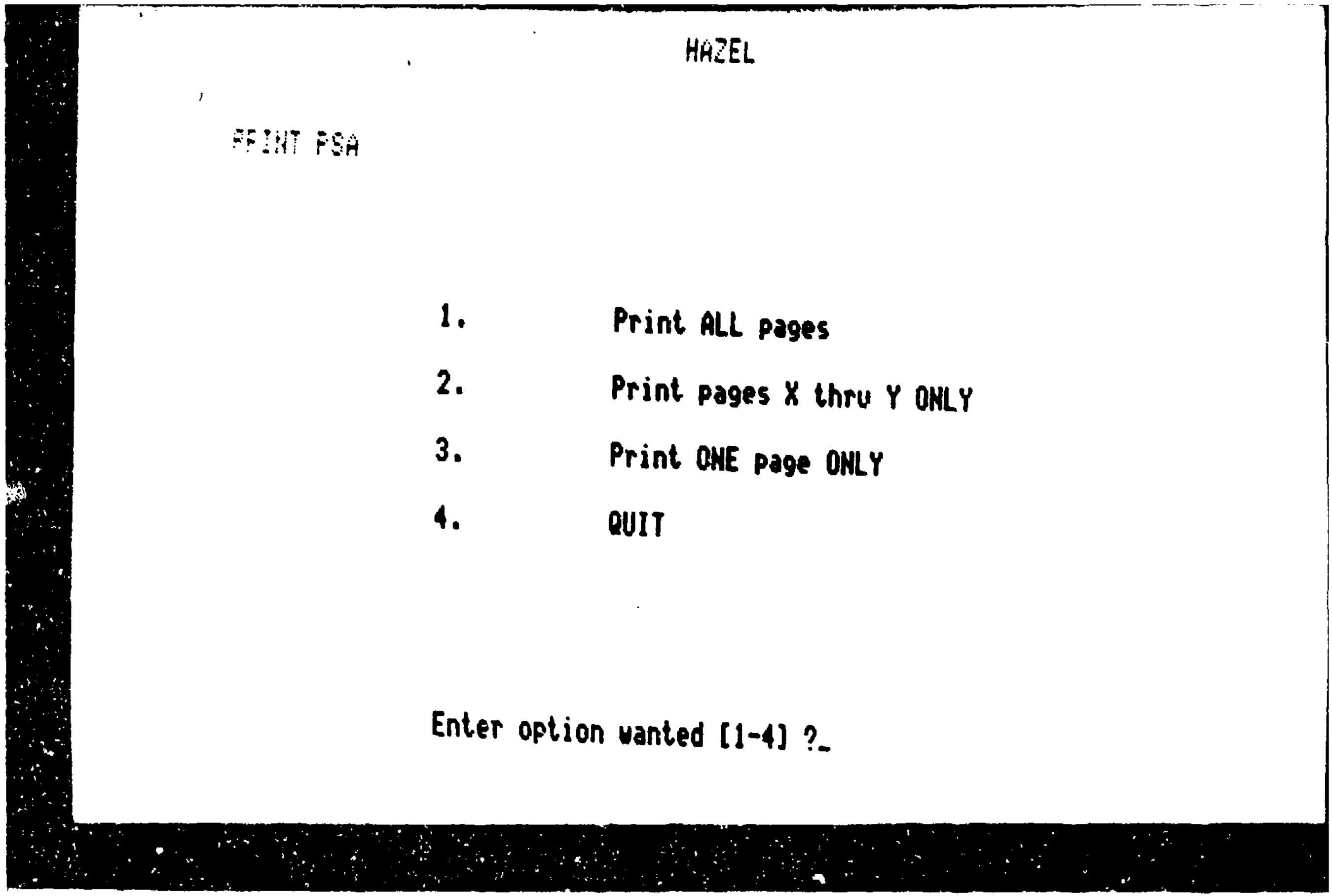
```
                                HAZEL
          REVIEW/UPDATE SAFETY ANALYSIS

                    1.  CLOSE THE HAZARD

                    2.  VERIFY THE HAZARD CLOSED

                    3.  REVIEW DATA ENTERED


                 Enter the option [1-3] ?
```

PSA SCREEN #11

This screen allows the hazard to be closed or closed and verified.

It, also, permits return to screen #10A if desired.

After this screen, HAZEL will request the HAZTAC disk to be placed in Drive A, in order to update its files and then load the master program.

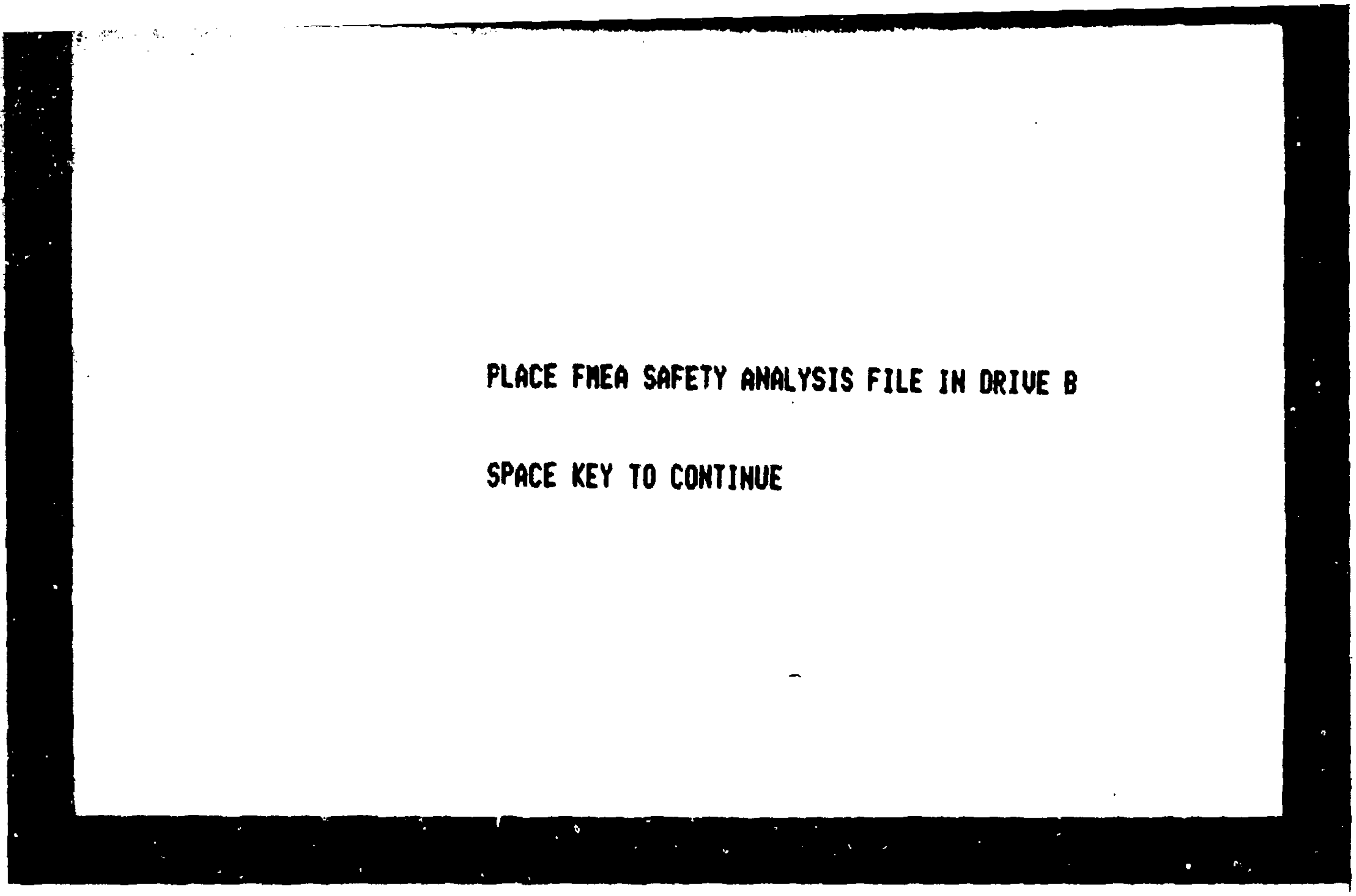


```
                                HAZEL

  PRINT PSA



                1.          Print ALL pages

                2.          Print pages X thru Y ONLY

                3.          Print ONE page ONLY

                4.          QUIT




                Enter option wanted [1-4] ?_
```

PSA SCREEN #12

The above menu is for the print option. The same basic procedures are required to reach it. However once the option is completed, this option does not require updating of the HAZTAC file.

It can be used to print any page or pages of the selected evaluation.



PLACE FMEA SAFETY ANALYSIS FILE IN DRIVE B

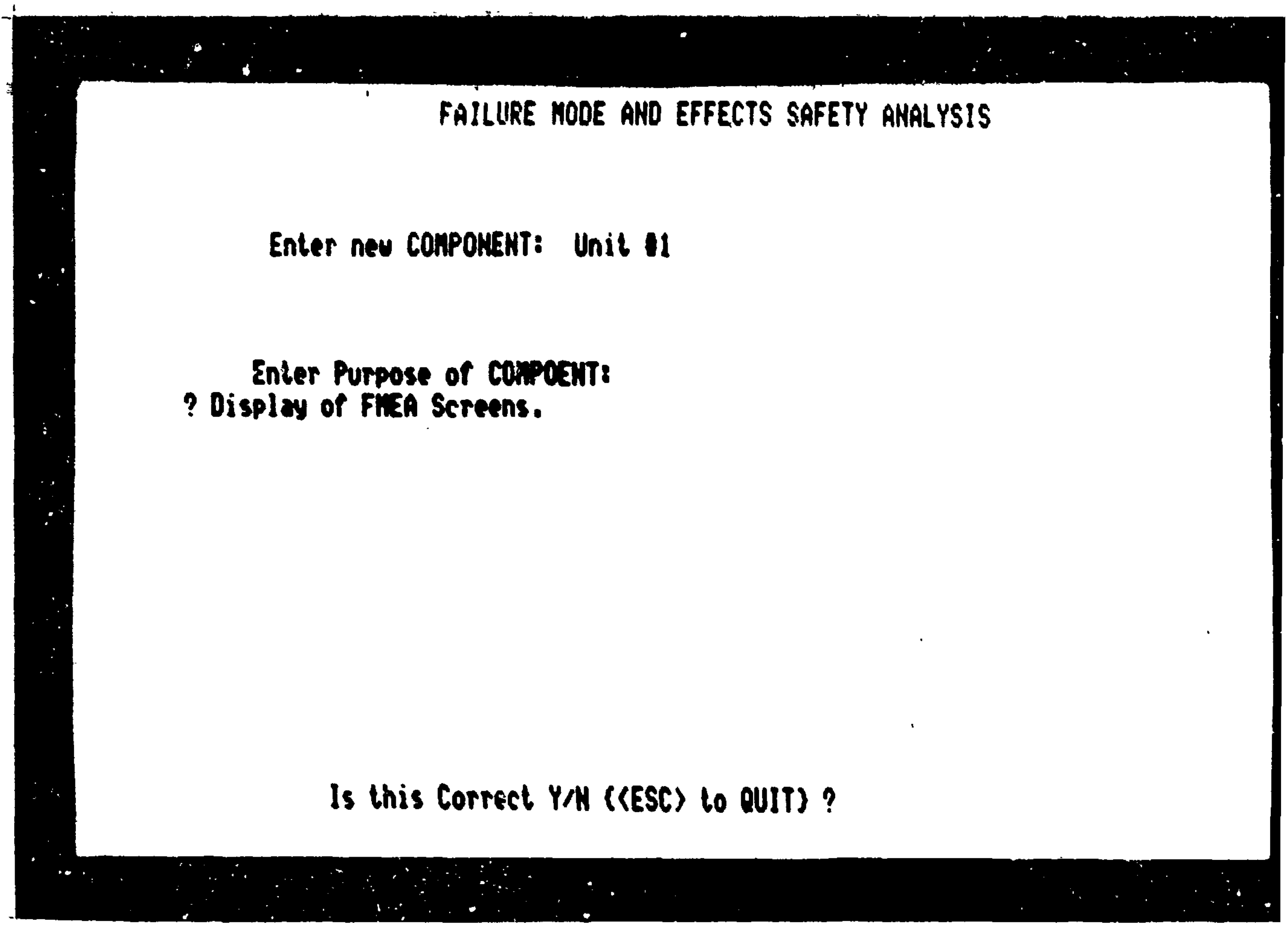
SPACE KEY TO CONTINUE

FMEA SCREEN #1

This is the first screen for the FMEA.

HAZEL would verify that the correct disk was placed in Drive B.

If the disk had not been used before, HAZEL would create the various files required.

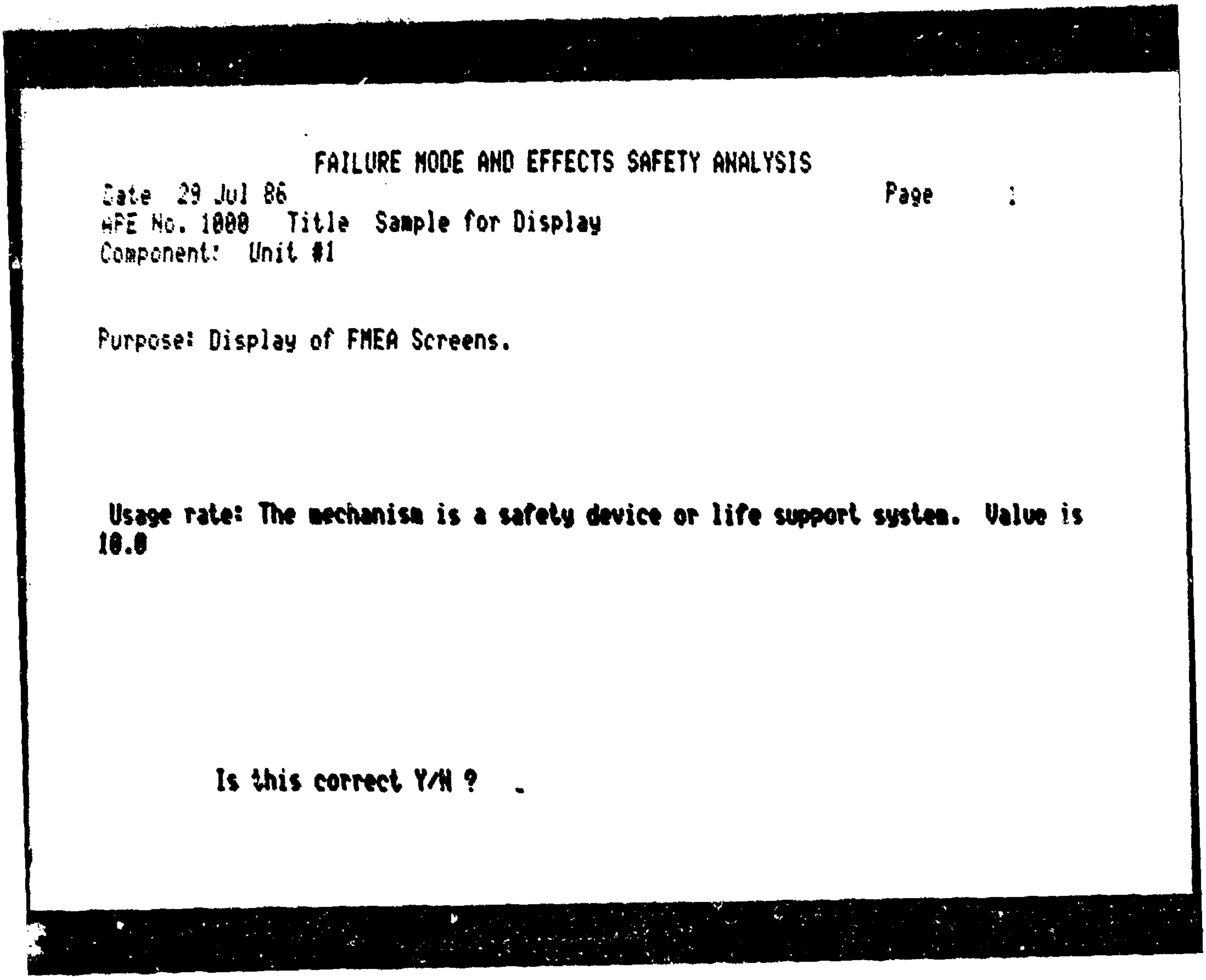


```
                    FAILURE MODE AND EFFECTS SAFETY ANALYSIS


        Enter new COMPONENT:  Unit #1


       Enter Purpose of COMPOENT:
    ? Display of FMEA Screens.





            Is this Correct Y/N (<ESC> to QUIT) ?
```

FMEA SCREEN #2

HAZEL then requires the item being evaluated and its purpose to be entered.

Once satisfied with the results and "Y" or "y" is entered, HAZEL proceeds to the next screen.

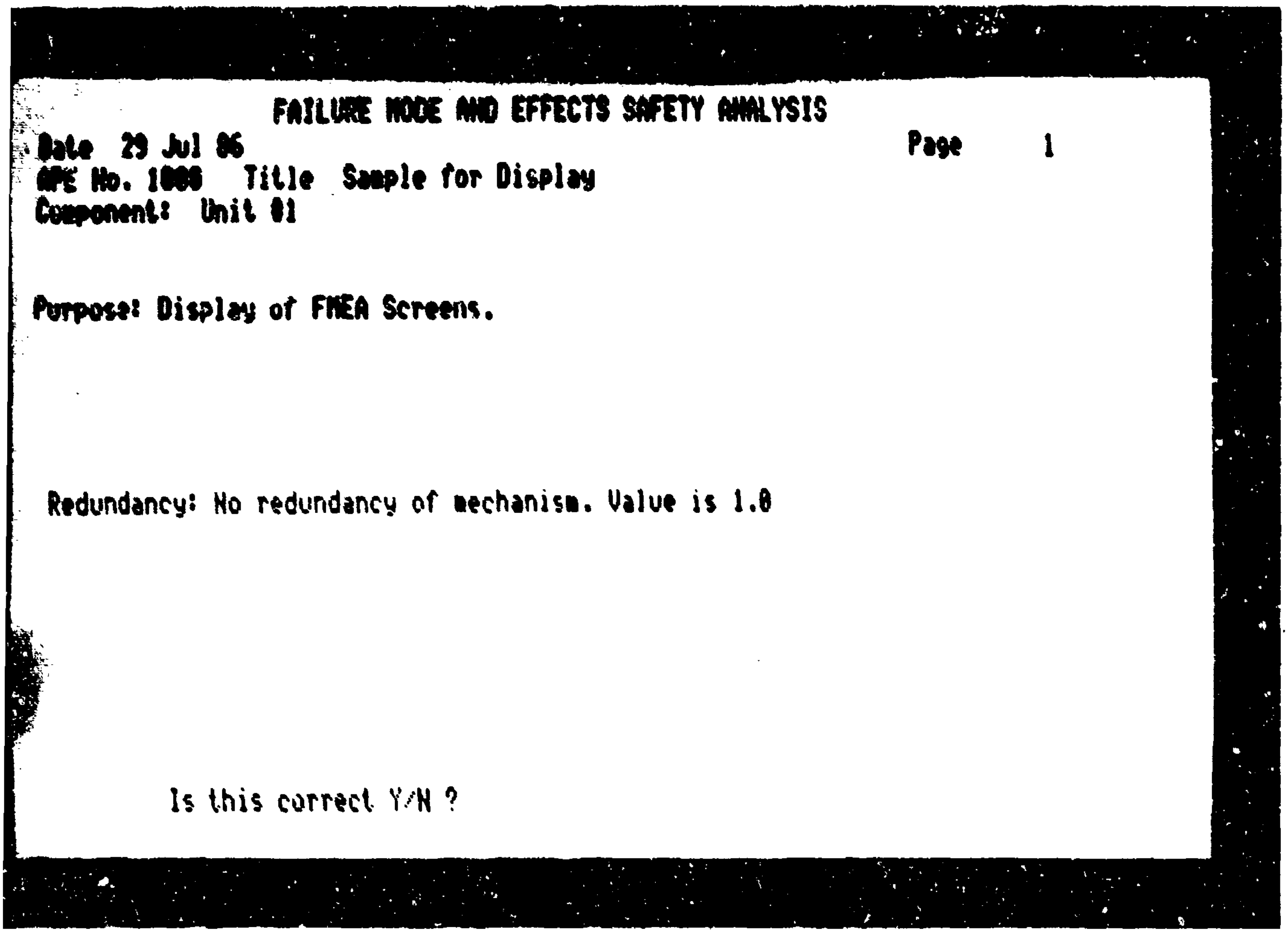


```
                    FAILURE MODE AND EFFECTS SAFETY ANALYSIS
Date  29 Jul 86                                                  Page      1
HFE No. 1000   Title  Sample for Display
Component:  Unit #1


Purpose: Display of FMEA Screens.




 Usage rate: The mechanism is a safety device or life support system.  Value is
10.0




        Is this correct Y/N ?   _
```

FMEA SCREEN #3

This screen determines the usage rate.

Once it is determined, HAZEL proceeds to the next screen.



FAILURE MODE AND EFFECTS SAFETY ANALYSIS

Date 29 Jul 86 Page 1

APE No. 1000 Title Sample for Display

Component: Unit 01

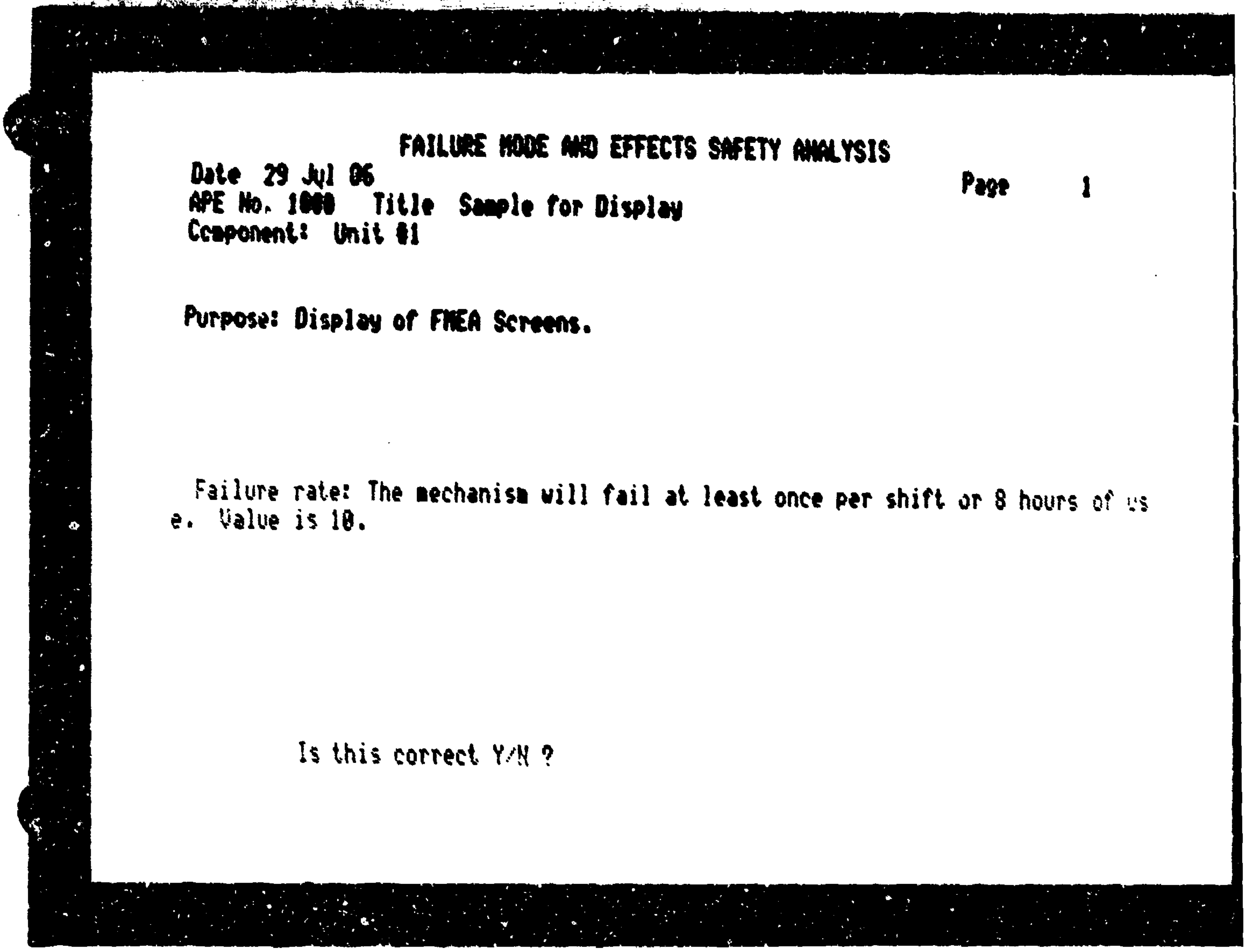
Purpose: Display of FMEA Screens.

Redundancy: No redundancy of mechanism. Value is 1.0

Is this correct Y/N ?

FMEA SCREEN #4

This screen determines the R factor or redundancy for the item. Once it is determined, HAZEL proceeds to the next screen.

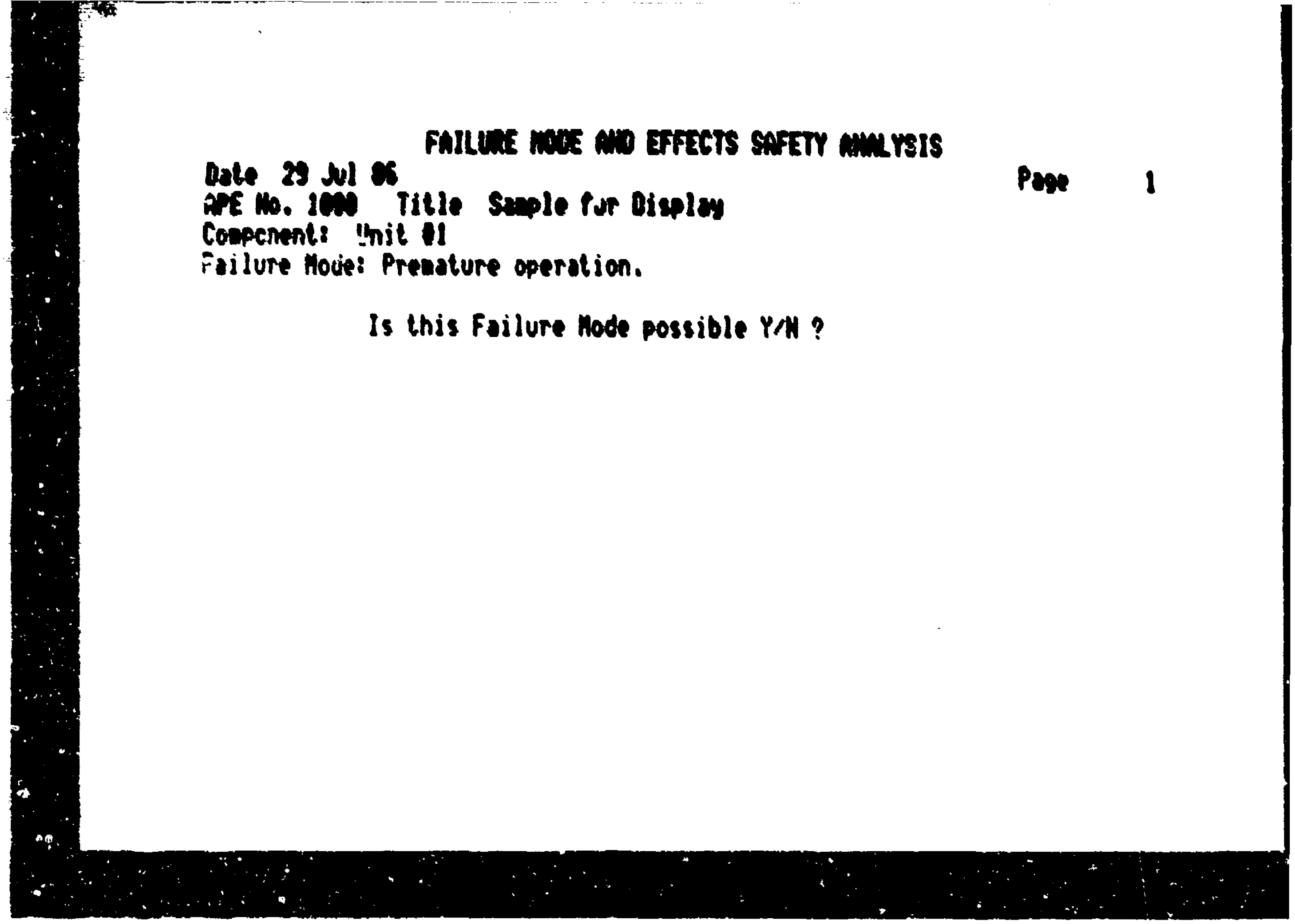


```
                 FAILURE MODE AND EFFECTS SAFETY ANALYSIS
Date  29 Jul 06                                              Page      1
APE No. 1000   Title  Sample for Display
Ccmponent:  Unit #1


Purpose: Display of FMEA Screens.




 Failure rate: The mechanism will fail at least once per shift or 8 hours of us
e.  Value is 10.






        Is this correct Y/N ?
```

FMEA SCREEN #5

This screen determines the failure rate for the item.

Once it is determined, HAZEL proceeds to the next screen.



FAILURE MODE AND EFFECTS SAFETY ANALYSIS

Date 29 Jul 86 Page 1
APE No. 1000 Title Sample for Display
Component: Unit #1
Failure Mode: Premature operation.

Is this Failure Mode possible Y/N ?

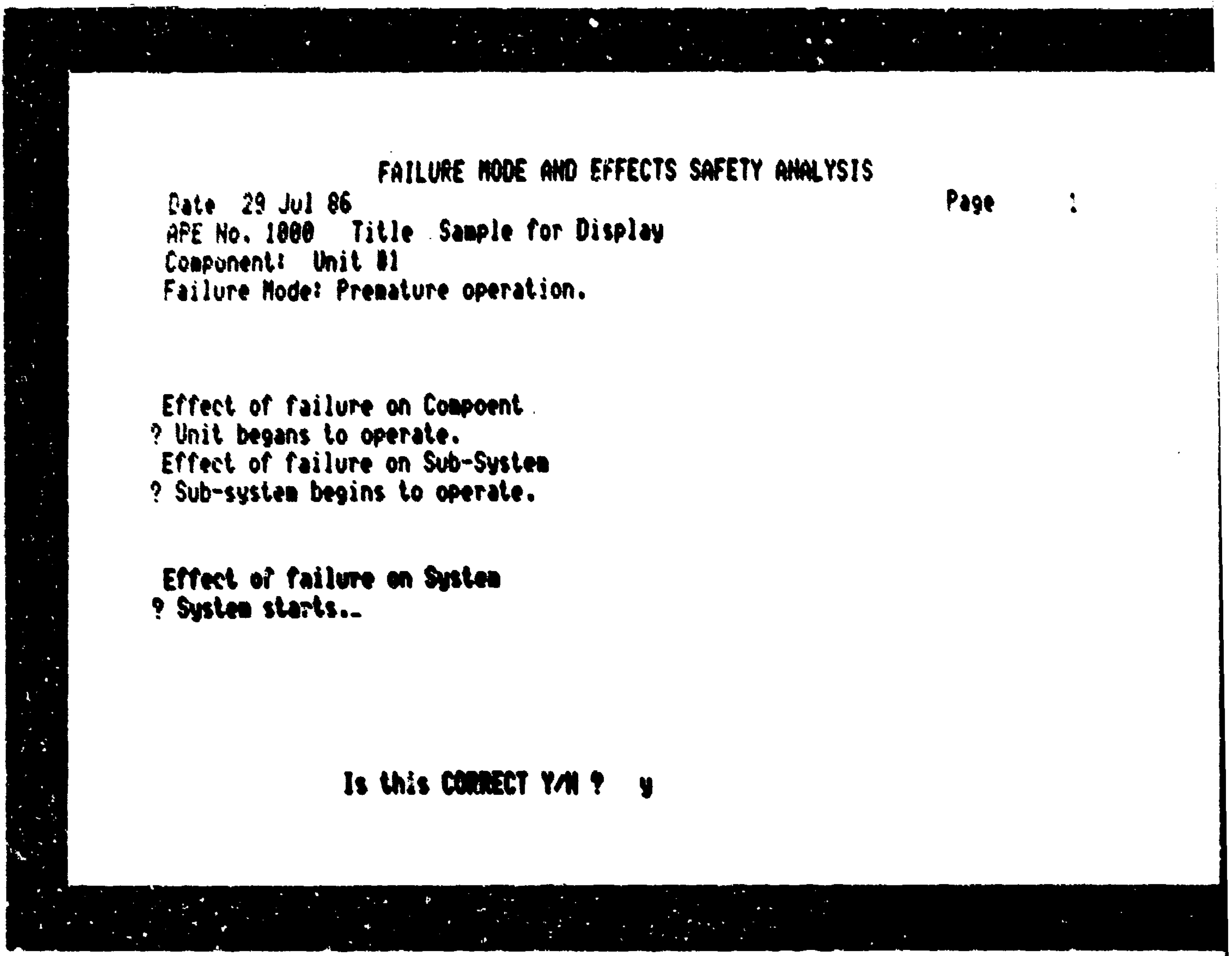
FMEA SCREEN #6

This screen represents the first of seven cycles which will be completed, one for each possible failure mode.

HAZEL asks if this failure mode is possible.

If not, HAZEL will continue with the next cycle until all modes have been evaluated.

If yes, HAZEL continues with this screen.

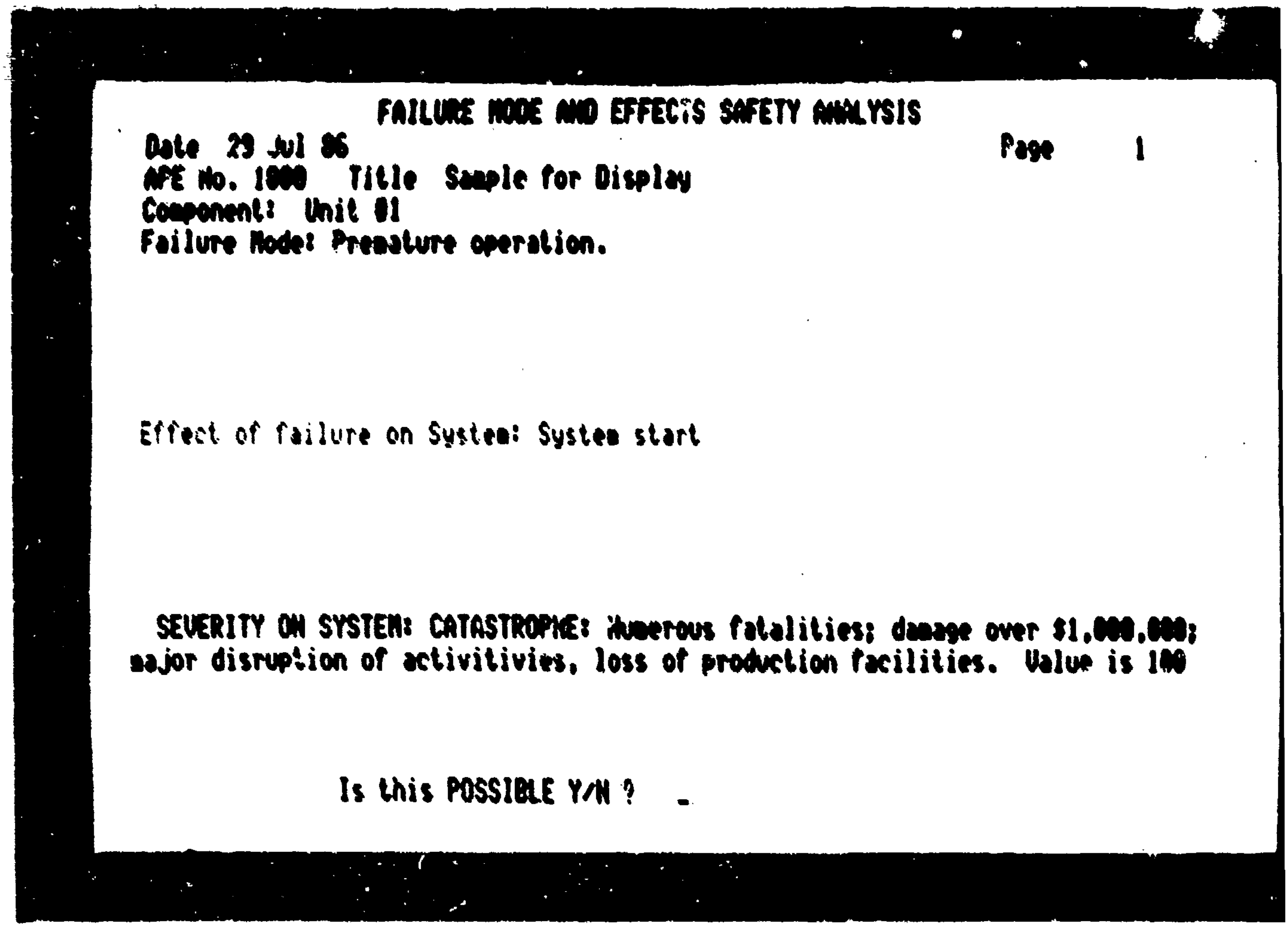


```
                 FAILURE MODE AND EFFECTS SAFETY ANALYSIS
  Date  29 Jul 86                                              Page      1
  APE No. 1000   Title  Sample for Display
  Component:  Unit #1
  Failure Mode: Premature operation.


 Effect of failure on Compoent
? Unit begans to operate.
 Effect of failure on Sub-System
? Sub-system begins to operate.


 Effect of failure on System
? System starts.._



               Is this CORRECT Y/N ?   y
```

FMEA SCREEN #6A

HAZEL will ask for the effect of this failure mode on the item, the sub-system to which it belongs, and the total system.

Once completed, HAZEL proceeds to the next portion of this screen.

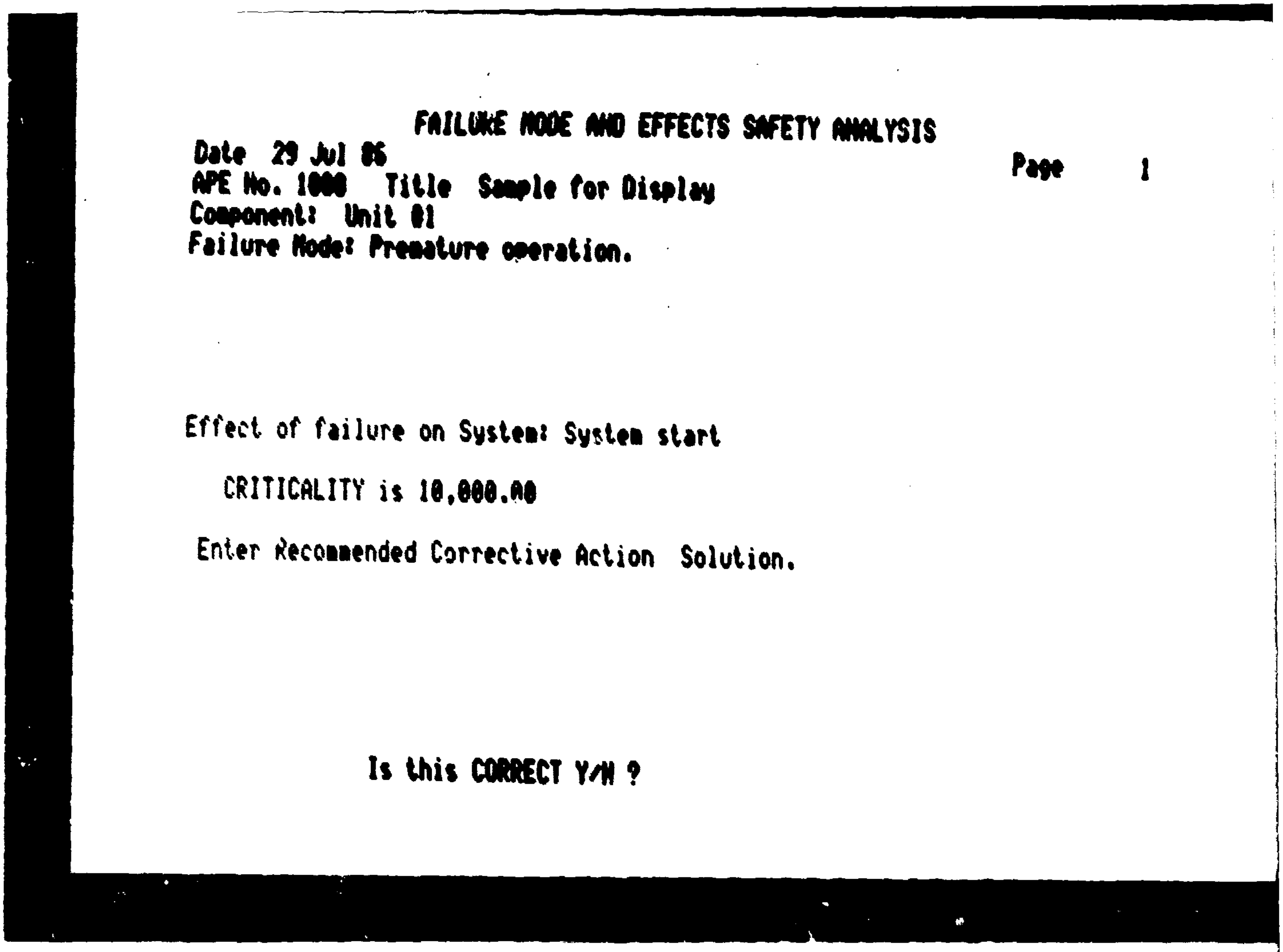


```
                  FAILURE MODE AND EFFECTS SAFETY ANALYSIS
Date  29 Jul 86                                                  Page     1
AFE No. 1000   Title  Sample for Display
Component:  Unit #1
Failure Mode: Premature operation.



Effect of failure on System: System start



 SEVERITY ON SYSTEM: CATASTROPHE: Numerous fatalities; damage over $1,000,000;
major disruption of activitivies, loss of production facilities.  Value is 100


                 Is this POSSIBLE Y/N ?  _
```

FMEA SCREEN #6B

This portion determines the severity of the failure on the total system.

Once completed, HAZEL proceeds to the next portion of this screen.

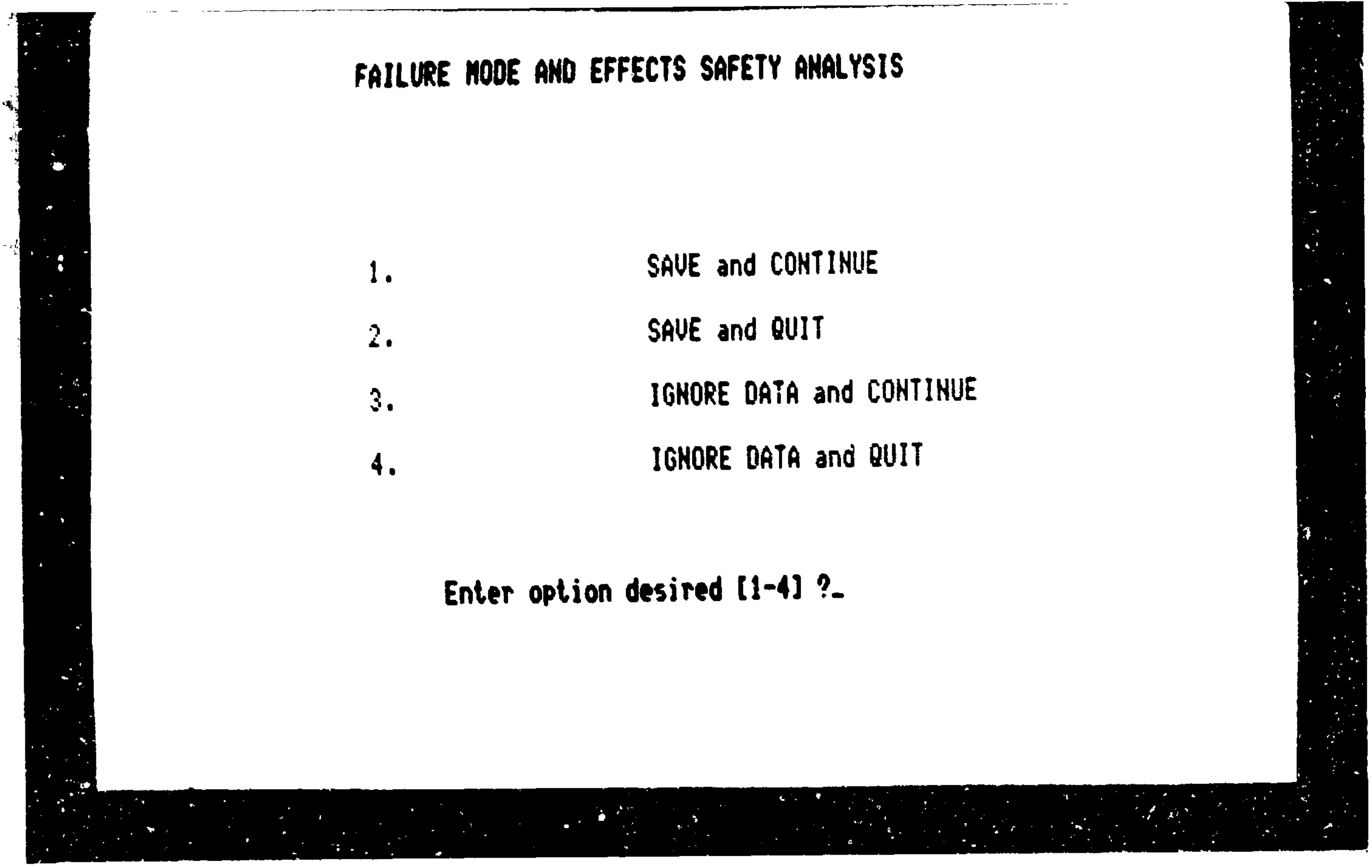


```
                    FAILURE MODE AND EFFECTS SAFETY ANALYSIS
Date  29 Jul 86                                                    Page      1
APE No. 1000   Title  Sample for Display
Component:  Unit 01
Failure Mode: Premature operation.



Effect of failure on System: System start

   CRITICALITY is 10,000.00

 Enter Recommended Corrective Action  Solution.




                 Is this CORRECT Y/N ?
```

FMEA SCREEN #6C

The criticality for the failure mode is displayed and if greater than 10, a recommended solution is requested.

Once completed, HAZEL proceeds to the next screen.



```
FAILURE MODE AND EFFECTS SAFETY ANALYSIS



1.                SAVE and CONTINUE

2.                SAVE and QUIT

3.                IGNORE DATA and CONTINUE

4.                IGNORE DATA and QUIT


      Enter option desired [1-4] ?_
```

FMEA SCREEN #7

This screen allows the data entered to be saved, and, also, offers the option of quitting.

If option 1 or 2 is selected, the data is saved and the the FMEA page is printed.

If option 3 or 4 is selected, the data is not saved.

If option 1 or 3 is selected, the next failure mode is considered.

If option 2 or 4 is selected, the HAZTAC file is updated as before, and the main program is loaded.

FINAL NOTE

Not all menus or screens are included, due to the number involved.

The menus and screens selected, however, represent how HAZEL flows, the built in checks incorporated, and how HAZEL interfaces with its user to allow corrections and rewording during her use.